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# **Optimal Route Planning with Mobile Nodes in Wireless Sensor Networks**

By

**Christopher Zygowski**

A Thesis

Submitted to the Faculty of Graduate Studies

Through the School of Computer Science

In Partial Fulfillment of the Requirements for

The Degree of Master of Science

At the University of Windsor

Windsor, Ontario, Canada

2018

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# **Optimal Route Planning with Mobile Nodes in Wireless Sensor Networks**

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September 11, 2018

# DECLARATION OF ORIGINALITY

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# ABSTRACT

Wireless Sensor Networks (WSN) are a collection of sensor nodes that sense their surroundings and relay their proximal information for further analysis. They utilize wireless communication technology to allow monitoring areas remotely. A major problem with WSNs is that the sensor nodes have a set sensing radius, which may not cover the entire field space. This issue would lead to an unreliable WSN that sometimes would not discover or report about events taking place in the field space. Researchers have focused on developing techniques for improving area coverage. These include allowing mobile sensor nodes to dynamically move towards coverage holes through the use of a path planning approach to solve issues such as maximizing area coverage. An approach is proposed in this thesis to maximize the area of network coverage by the WSN through a Mixed Integer Linear Programming (MILP) formulation which utilizes both static and mobile nodes. The mobile nodes are capable of travelling across the area of interest, to cover empty ‘holes’ (i.e. regions not covered by any of the static nodes) in a WSN. The goal is to find successive positions of the mobile node through the network, in order to maximize the network area coverage, or achieve a specified level of coverage while minimizing the number of iterations taken. Simulations of the formulation on small WSNs show promising results in terms of both objectives.

# DEDICATION

I dedicate this thesis to my parents Krystyna Zygorvska and Arkadiusz Zygorvski, for their motivation and blessings without which I would not have made it this far . To my siblings Alexandra and Dominika who support me and pushed me to keep going.

# ACKNOWLEDGEMENTS

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I would also like to thank my remaining committee members Dr. Scott Goodwin and Dr. Fazle Baki for their help and support.

I would like to thank my family and friends for sticking with me and supporting me.

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# ABBREVIATIONS

WSN	Wireless Sensor Network
MILP	Mixed Integer Linear Programming

# CHAPTER 1

## Introduction

### 1.1 Introduction of Wireless Sensor Networks

Wireless Sensor Networks (WSNs) are networks composed of a set of sensor nodes communicating amongst themselves and a data collection center [1]. One of the main functions of WSNs is to supervise particular changes in an environment and report any results for further analysis [1]. The wireless sensor nodes, which compose WSNs, collaborate to jointly perform sensing tasks on a larger scale. Recent advancements in microprocessors, electro-mechanics and wireless communication allow for the design of smaller and lower cost sensor nodes. This, in turn, leads to an easier access to the construction of large WSNs [2].

In this thesis, the sensor nodes of WSNs are assumed to be small battery-powered autonomous devices able to collect information regarding their immediate vicinity through attached sensors [3][4]. The information acquired is processed locally and then communicated to a data collection center, also known as a base station or sink. Specifically, the sensor nodes are typically equipped with a sensing unit for data acquisition, a basic processing unit with limited computational power and a wireless communication unit onboard. Each of these components have limited capabilities including memory for data collection, energy for operation and bandwidth for wireless communication [1][5].

## 1.2 Thesis Overview

WSNs are widely used for monitoring large areas for conditional changes. In many scenarios, sensor nodes are used as stationary sentries after their initial deployment. This initial network configuration can be used to compute the current network coverage. However, this approach may lead to overlapping redundant node coverage depending on the initial condition of the static nodes. Following this step will be the deployment of mobile sensor nodes, which will have the capabilities of movement to the areas which are not yet covered by static sensor nodes. However, equipping every node with movement capabilities increases the network cost and may lead to collisions. Thus a limited amount of mobile nodes are utilized to keep a balance between overall coverage and sensor node cost.

## 1.3 Methods and Software

In order to accomplish the task of optimizing the total area covered by all sensor nodes, the setup of the WSN is first determined. A set of non-relocatable static sensor nodes will be randomly deployed in the given area. Accompanying these static nodes will be a small subset of mobile sensor nodes which will be able to modify their position while being subject to mobility constraints. Using their controlled mobility, these mobile nodes will provide coverage to areas which are not in the sensing radius of the static nodes [1]. The goal reached is to utilize and exploit the manoeuvrability of these mobile nodes in order to optimize the total sensing coverage possible in the least number of time steps, given the infrastructure.

There have been various algorithms proposed which determine mobile sensor nodes movements such that they move to uncovered areas in order to attain a more balanced coverage. The main difference between these approaches lies in how the algorithms compute the positions of the sensor nodes and the behaviour of movement of the mobile nodes. The objective of mobile

node path finding, is no different to previous approaches, however, the method used to accomplish the task is original. Static sensor nodes are first placed in the desired area while a Mixed Integer Linear Programming (MILP) Formulation is utilized to determine the optimal path the mobile node should take to achieve an optimal area coverage.

## **1.4 Motivation**

Utilizing mobile nodes to cover areas, which are uncovered in the desired search space, will reduce the possibility of data being missed in areas that were not yet covered. In many scenarios, static sensor nodes may not be distributed into a desired location [6][7]. The target field may be a hostile environment with uncontrollable factors such as obstacles or wind which will affect the initial deployment in the target area. Finding an optimal path that these mobile nodes will take to optimize area coverage is also very important to various application fields.

The addition of mobile nodes aids many different application fields such as civil application like health care, security, environmental monitoring and also military applications [2][8]. These fields can be categorized into resource management (such as in data centers), remote monitoring, target tracking and event detection. For applications in health care, wireless sensor networks can provide less invasive patient monitoring and health care possible. These networks are also helpful for security systems which includes intrusion detection through patrolling alarms, military surveillance and can be attached to people or vehicles to protect them from unnecessary circumstances. Finally, WSNs are also very helpful for environmental monitoring including the sensing of unnatural conditions such as pollution in the air, water or soil of a given area. The addition of dynamically patrolling sensor nodes [3] to static node WSNs may be used for these types of applications to increase their performance and reliability.

## 1.5 Problem Statement

Research on WSNs has evolved over time. Initially, the strategy for deployment of sensor nodes was to simply place more and more until the problem requirements were reached [9]. This initial process is inefficient since the addition of an increasing number of nodes leads to a prohibitive cost, not only monetary but also in other factors such as steeper deployment, management and maintenance costs [10]. Lastly, adding more nodes may lead to a number of redundant nodes which may overlap in their sensing radius'. Mobile nodes are utilized in order to circumvent these problems and other similar issues.

This thesis experiments on the use of mobile nodes in the context of WSNs to solve problems dealing with area coverage. These problems include allowing the WSN to handle instances where there may be random failures of nodes while keeping energy efficiency and coverage efficiency in mind [11]. These problems are all with regards to keeping as good a coverage of the target area as possible for as long as possible. Random failure of a given set of the nodes can lead to *coverage holes* [11][12], which in turn will need to be covered by mobile nodes. On the other hand, sensor nodes have a limited battery power, thus energy usage of the mobile nodes must be taken into account when planning mobile node paths. The path planning is conducted in such a way that the route taken by mobile nodes is covering the maximal number of coverage holes in the least amount of time.

The main problem being addressed is of increasing area coverage by exploiting mobility of mobile nodes in WSNs. Coverage of the given area is a significant issue when deciding on the deployment and performance of the WSN. The surveillance quality or total coverage monitored by the sensor nodes signifies how well the region is monitored and how effectively the WSN detects environmental changes. An optimal area coverage by the WSN will result in the

reduction of blind zones, or coverage holes, and redundant coverage of overlapping sensing radius' of sensor nodes. This thesis specifically maximizes an optimal area coverage of the search space in the least number of iterations. Event detection is a large component of the applications using WSNs which relies heavily on area coverage. In event detection, sensors must be able to reliably detect an event in the given search space. Thus, an optimal area coverage by the mobile nodes is necessary to assure accurate detection of transpiring events [6][7].

A large factor of this thesis is understanding the various network parameters necessary to improve the coverage of wireless sensor nodes depending on varying scenarios. Specifically, this thesis addresses the following questions:

1. What is a sufficient condition for an optimal area coverage using a WSN?
2. How can we design an MILP formulation for sparse and highly dense deployed WSNs in order to guarantee maximum area coverage with a minimum number of mobile node movements?

## **1.6 Solution Outline**

In order to overcome the above-mentioned problems, there have been many previous attempts to alleviate them including increasing the number of static nodes [7] or adding sensor nodes which have a larger sensing radius [11]. Both of these approaches have the problem of increasing cost by adding these nodes to the infrastructure. To circumvent these issues, this thesis proposes using mobile sensor nodes in an optimally found path. The combination of static and mobile sensor nodes in tandem is termed a mixed WSN [1][11][13]. In the literature, mobile nodes are moved either by a dynamic path planning approach or in a deterministic fashion with a set of rules to constrain the movement of the mobile nodes [9][11][14]. In our thesis, the mobile

nodes are routed through the search space grid using a MILP formulation to determine the optimal path the mobile node should take to achieve complete grid area coverage.

This thesis, uses mobile nodes in a deterministic fashion, in which the optimal movement path of the mobile nodes is determined based on the initial random deployment. A dynamic or random movement pattern for mobile nodes is not handled in this thesis. The mobile nodes are mainly treated as nodes used to 'heal' uncovered areas which are not yet covered by static nodes. They may also have to collaborate with the static nodes, since some static nodes may fail. Thus the mobile node must take these situations into account when determining an optimal path to maximize coverage.

Mobile nodes are sensor nodes mounted on a mobile robot. They will be used to increase the area of coverage which will lead to a lesser probability that an event or change in the environment is missed and hopefully minimize the time taken to report an event. Furthermore, the introduction of mobility will allow for the WSN to react better to inaccurate initial node deployment and possible node failure. Since the number of mobile nodes is usually a small fraction of the total amount of sensor nodes, the added cost is very minute. Not only do mobile nodes aid in fault tolerance, reliability and increasing overall coverage, but they also reduce the cost compared to a dense deployment of sensor nodes or the extra cost of forcing the initial deployment into an optimal condition.

Specifically, this thesis introduces MILP formulations which guide mobile nodes along an optimal path, such that the maximum coverage of uncovered areas is achieved in the least number of time steps.



## **1.7 Thesis Organization**

The remainder of the thesis is structured as follows. Chapter 2 reviews literature work related to maximizing area coverage using sensor networks. This section will also act as an overview of the terminology used with WSNs and important concepts such as the assumptions specified. Chapter 3 highlights the contributions of this thesis. This includes the proposed approach used, the network model used and a comparison of area coverage and mobile node time step usage against existing approaches. Chapter 4 outlines simulation results. This section will go over the simulation setup, a comparison of results and give a general grading on how well the algorithm performed. Chapter 5 will conclude the thesis with a summary of the main topics of the thesis, along with possible future work.

# CHAPTER 2

## Literature in the Research Area

### 2.1 Overview of Broad Research

This thesis' presented work is related with two main research fields. They include maximizing area coverage in WSNs and path planning [11][15][16]. Wireless Sensor Networks (WSNs) are networks consisting of nodes communicating amongst themselves. Research topics using WSNs usually consist of supervising and reporting on particular environmental changes. In order to circumvent problems regarding coverage holes [2][6][9][17], connectivity [3][11][18][19], and energy efficiency [20][21][22] mobility was added as a research area for WSNs. The introduction of mobile nodes in WSN [23][24] not only added a new outlet for innovation, but also necessitated the development of suitable path planning approaches, for the mobile nodes. Path planning has been investigated from multiple angles when dealing with sensor node mobility. Whether the path planning method is being used to cover uncovered areas or simply to move around obstacles, they all have their advantages and resultant downsides [15][16].

From the first general solutions of using WSNs, which included simply adding more sensor nodes to the search space or formulating smart deployment strategies; the novelty of mobility as an addition to WSNs has shown much promise [3][23]. Whether dealing with uncontrollable aspects of the environment or adding new functions to an older idea, manoeuvrability of sensor nodes allows for growth in multiple application types such as event

detection and remote monitoring. Research on mobility in WSNs can be found in all aspects of daily life. From health care to environmental monitoring to military operations, mobile WSNs have been used to solve or improve existing solutions for many facets of each of these fields.

## 2.2 Basic Terminology

Some terms which will be used on multiple occasions during this thesis are:

**Wireless Sensor Network (WSN) :** These networks use wirelessly communicating nodes to relay information between each other. The nodes have sensors attached to them which allow for reading and logging information regarding its adjacent environment. The use of mobile nodes in WSNs is studied in this thesis [1][5][7][11].

**Area Coverage :** is the ratio of area which is within the sensing radius of sensor nodes in a WSN versus the total area of the search space. Total area coverage means that every cell within the monitoring field is covered by at least one sensor node's sensing radius [4][6].

**Network Topology :** is an outline denoting the communication connections between the nodes of a WSN. In general, the topology shows which nodes can relay information to other components of the network [4][12].

**Sensor Node :** Stationary nodes are the backbone of WSNs. They are the devices with capabilities to wirelessly communicate to other node devices in the network. These devices are also equipped with sensors. The sensors installed have a wide variety of uses such as measuring temperature changes, pollution levels, detecting movement changes and for basically any application field in need of event detection or remote monitoring. Recently, sensor nodes have also been equipped with manoeuvring capabilities which allows for mobile sensor nodes [1][3][5][15].

**Data Center :** is the processing center of the WSN. It houses the information gathered from the search space and analyzes it so that the useful information is used to solve real world problems.

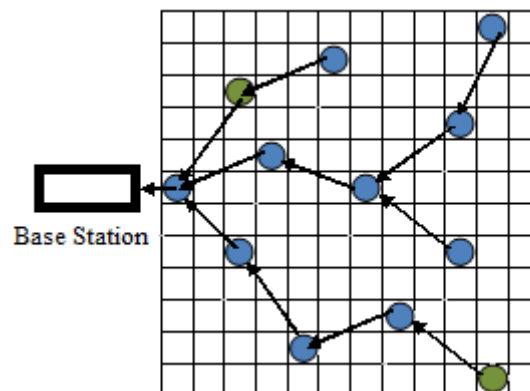
Base station and sink are both terms used to describe a data center [1][25].

**Data Collector Node :** is an intermediate node between the data center and the sensor nodes. It is mainly used to collect information from sensor nodes and then will relay it to the data center [1][26].

**Communication Radius :** is the distance around a node at which it can send and receive messages. If the distance between two nodes exceeds the communication range, they will not detect one another and will not be able to relay message between themselves [1][7].

**Sensing Radius :** is the distance around a node that it is able to sense changes in its environment. Similarly to communication radius, the node cannot sense or report fluctuations outside of its sensing radius [1][7].

**Multi-hop routing :** is the way in which sensor nodes can pass their gathered information along other sensor nodes to reach the data center as displayed in Figure 1. Specific nodes are sometimes added in WSNs as a possible collector of the data which is passed through multi-hop routing. This routing is mainly used when the sensor nodes are not in communication range of the data center [3].



**Figure 1. Example of Messages Relayed through Multi-hop Routing**

**Euclidean distance:** is a measurement of distance. For reference, this distance is between two points  $(x_1, y_1)$  and  $(x_2, y_2)$  in a two dimensional plane given by the formula

$$\sqrt{(x_1 - x_2)^2 + (y_1 - y_2)^2} \text{ [7][14].}$$

**Centroid :** is the average taken for all the positions of all the points or nodes. All the coordinate directions are taken into account when determining this "center" point in relation to all the nodes [26].

**Cluster :** is a grouping of objects. This group will usually have a cluster-head which is the authority object that determines how and what information is passed between the objects in the cluster. Clusters are usually formed based on proximity. This means that objects that are closer to one another will usually form a cluster and those that are far apart will be usually part of different clusters [4].

**Mixed Integer Linear Programming (MILP) :** is a mathematical optimization program using integer and binary variables to formulate a sequence of equations. These equations will be used in tandem to create something called a formulation. This formulation must have an objective function, which the MILP will either try to maximize or minimize towards. It will also contain constraint equations which will limit the upper and lower values of the variables. The constraints must limit the objective function as well, so that an objective value can be reached [27].

**CPLEX:** is an optimization software. Specifically it is a mathematical programming solver for linear, quadratic and mixed integer programming. Linear and Quadratic programming both share similar traits to MILPs, however they allow linear and quadratic equations respectively [25].

**Bidding protocols :** are method in which one decision maker will make a decision based on the aggregated information from other decision makers. One node will act as a decision maker and broadcast an "auction message" to other nodes. This auction message will detail information

which interests the decision node and ask for the other nodes' input. The decision node will wait an allotted time to wait for all the other nodes to send back their known information on the subject. Each other node will send this as a "bid." Once the time is up, the decision node will stop the auction and will choose between the information it has gathered to determine a suitable decision to make [1][10].

**Voronoi Diagram :** are structures which represent proximity information for a set of points or nodes. The method used is to partition the search space into cells such that the area in a cell surrounding a sensor node is closest to that node and no other. Thus the segmented area is basically the search space broken up into sections which surround each sensor node [10][28].

**Path Planning :** is an approach which determines the path a node moves along in the given area of interest. Varying factors in the space surrounding a node can persuade the node to move in a certain direction. The way in which the path is determined may be pre-determined or dynamically changed [2][9][11].

## 2.3 Fundamental concepts

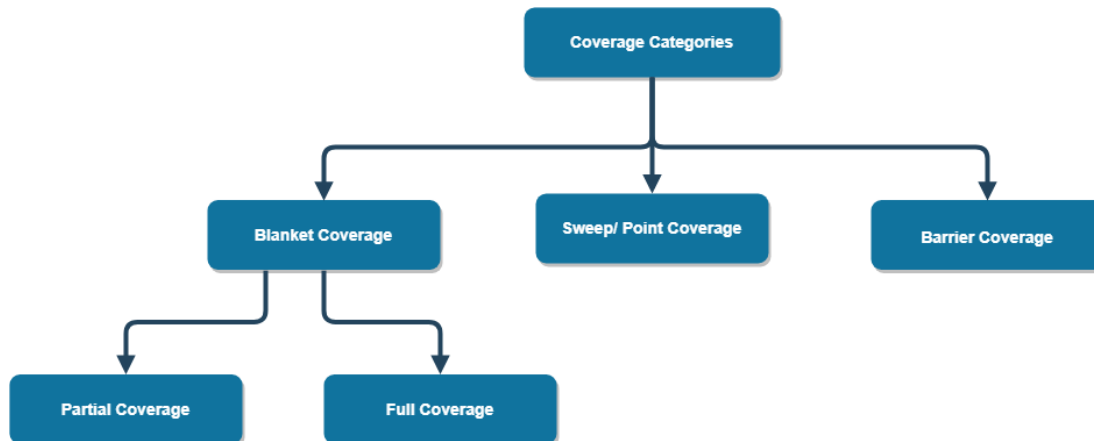
WSNs are a deployment of sensor nodes in a specific region or area. The sensor nodes are specifically designed to capture some type of environmental change. These network nodes are distributed such that events will be tracked or detected with the highest accuracy. The sensor nodes are able to communicate this information to any of the components of a WSN. These components include other sensor nodes for multi-hop routing, a data collector node for quicker relay of data to the data center or to the data center directly for further data processing.

There are three main topologies which are Star, Tree and Mesh. The Star topology denotes a network where each node connects to the data sink directly. This method allows for quick access to the sink but limits node interaction. The Tree topology allows for nodes to be

connected in a hierarchical structure. The root or top of the hierarchy is the data center, which allows the connected nodes to feed forward information through other nodes in the hierarchy towards the sink. The Mesh topology constructs a network where each node can connect to several other nodes including the sink. This method allows for greater node interaction for dynamic approaches.

The ways which the components of a network communicate amongst one another may vary depending on the application. For many applications, there are one of two main problems which are solved. These are elongating the lifetime of the network through energy efficiency and increasing area coverage of the WSN. In order to decrease energy usage many approaches try to spread the usage of the components of the WSN so that one component is not excessively used and draining its energy. This is mainly for applications which have constant communication among sensor nodes.

This thesis mainly focuses on the improvement of area coverage and the reduction of coverage holes through mobility of sensor nodes. When speaking of research on coverage improvements through mobile nodes in WSNs, the different categories of area coverage must be defined. The various types of coverage are "blanket coverage, barrier coverage, sweep coverage and partial coverage" [29][30] and are displayed in Figure 2.



**Figure 2. Classification of Coverage Categories**

Blanket coverage is the term used to describe the requirement that the entire search space is monitored. Degree of coverage is a variable used to represent the ability of the WSN to cover the search space. It is the ratio of the space which is covered by sensor node's sensing radius' against the total space of the monitoring area. A degree of coverage of one symbolizes that the whole area is monitored by at least one sensor node. The higher the degree is, the more area is covered by sensor nodes. This means that some subspaces will also have overlapping sensing radius coverage, which may be necessary for some types of applications. A high degree of coverage may be essential to an application which monitors vital facilities with disastrous downsides to fluctuations. While different applications will require different degrees of coverage, a degree of coverage of at least one is usually the bare minimum. This type of coverage is useful for hostile environments where the monitoring of the environment is crucial. This could be helpful for applications such as monitoring volcano activity where the consequences of a missed event could lead to fatal consequences. Another specific example of this type of coverage could be habitat monitoring of wild animals which would allow for constant supervision of the wildlife [29][31].

Barrier coverage deals with a perimeter or boundary coverage where the WSN is deployed on the border of a given application space. Thus the whole area is not needed to be covered, since entry and exit from the area of interest is monitored. The sensor nodes of the WSN are usually desired to overlap their sensing radius with adjacent nodes' sensing radius'. This is so that any condition such as movement which may occur in the surveillance node area will be sensed with a higher chance of less false alarms or missed events. The main usage of this type of coverage is for event detection and security. Applications include monitoring entry of



illegal unwanted agents in a warehouse or facility and detecting the amount of traffic driving through a certain road [29].

Sweep coverage refers to applications with certain "points of interest" (POI) which have significant strategic value and must be monitored thoroughly. These coverage problems must guarantee that these POIs are covered during a certain time frame so that the important information needed is relayed without fail. This type of coverage is used for application such as one using weather buoys which are introduced in bodies of water to collect environmental data of their surroundings. Other applications of sweep coverage can include detection of the spread of forest fires, military patrol operations and monitoring along sections of pipelines for any faults along the pipes [29].

Partial coverage is essentially a subsection of blanket coverage. The difference between the two is that instead of striving for a degree of coverage, partial coverage only desires that resultant coverage is greater than a particular predetermined value. This type of coverage is mainly used for applications which need a general sampling of the search space rather than a rigorous accounting for the entire space [29].

These categories of coverage are present in any real world application. The way in which an algorithm uses environment information to setup a WSN will determine its performance when attempting to optimize one of these types of coverage. Beyond the initial setup of the WSN is the setup of an algorithm for fault tolerance and to handle irregularities in the search space grid.

A general approach to circumvent issues after initial deployment of a WSN is to use a path planning technique. As noted above, this is the way a route is set in place for the mobile node to take during the next set of time steps. Different factors such as energy consumption, area coverage and obstacle avoidance are all optimized in some way so that a better path planning

technique is created. An important aspect of path planning to understand is the various dynamic and deterministic approaches that can be used. Below are different techniques and path planning approaches that are found in the literature.

**Grid Scan Algorithm:** will sample each cell in the search space one by one. During this runtime, a particular trait will be investigated and set as a variable to be used later. This algorithm is used in other area coverage approaches. An example usage would be for helping mobile nodes determine whether each cell has been covered by a static node's sensing radius. Cells which are uncovered will be set to a base value for future reference in a variable. Those uncovered nodes which are surrounded by other nodes, which are uncovered, will increase their value according to how many nodes they are surrounded by and those nodes' values. These final values will indicate how large the coverage holes are depending on which cell is queried. The mobile nodes will each run this algorithm to find the closest coverage hole in their vicinity [2][9].

**One scan algorithm :** is a heuristic used to improve the performance of the Grid Scan algorithm.

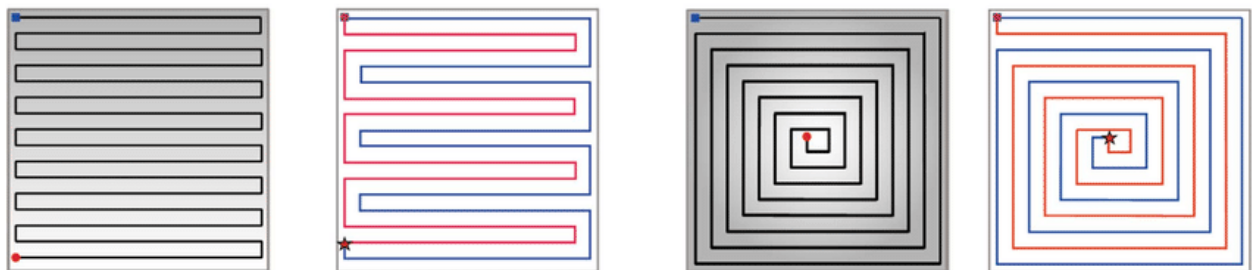
This algorithm will disregard mobile nodes until the final step of the process. While the Grid Scan approach will run for each mobile node, the One Scan approach will simply run over each cell and store their values. The coverage holes which are found will still be ranked by their size. At the last step, the mobile nodes will check their immediate surroundings for information regarding coverage holes. They will also update the value of the cells which they will be covering [2].

**Zoom algorithm :** is a divide and conquer approach. First the grid is split into four parts and each part is checked for their total amount of uncovered nodes. The sector with the most uncovered cells is chosen as the new subspace. This is repeated until an entire subspace is only uncovered

cells. This area will be labelled with a variable as the largest coverage hole. The algorithm will then be used again until all coverage holes are ranked from largest to smallest [1][2][9][11].

**Game theory :** is an approach where a model is created to study the cooperation and conflict between decision makers. The decision makers are ultimately tasked with optimizing a criteria for their own benefit. The interactions between the decision makers and their attempts to optimize their criteria shows emergent properties as to their optimal strategies to beat their opponent [6].

**"Standard" Deterministic Path Planning :** uses a schema at the first time step to pre-determine where the mobile node should move to at any given future time step. This schema is simply to move the mobile node far enough that it will cover as much new cells as possible, while also not leaving coverage holes in the places it has passed. These types of approaches do not take into account other static node coverage and do not use logic to determine the route. They will simply move in a certain direction until an area boundary is met and then will turn towards a perpendicular direction and continue movement [11].



**Figure 3. Standard Deterministic Path Planning Approaches [32]**

**Receding horizon algorithm :** is a particular path planning approach allows a node to estimate a set of future positions it may move to at each time step. The set of positions which the node may move to is called a "cognitive map." From this cognitive map, a decision can be made as to

which position to move to based on various parameters such as coverage or energy usage [2][9][11].

**Potential Fields** : is a concept where each node is imagined to have an invisible field around itself.

The node will be repelled when it is near obstacles or other nodes which are within this field. A "friction force" is added as well which will slow the node drastically after it begins to move. The node will still be able to move away from other objects within its potential field, but will quickly come to a halt after the object moves out of reach of the nodes field [14].

## 2.4 Current Research Issues in WSNs

In regards to WSNs, there have been many advancements and approaches proposed, in order to circumvent issues such as coverage capability and energy efficiency. Recent use of mobility of nodes in WSN has led to the creation of some innovative techniques to solve a variety of issues.

A recent category of work being done on WSNs is regarding data collection and transfer between the components of the network. These strategies aim to generally increase the lifetime of the network's nodes by spreading the load of node usage equally across all the network components. Furthermore, they aspire to assist the network in relaying information in an optimal manner. This is done so that information will be transferred within a timely manner and the data is not lost before reaching the data center.

Some recent papers on data gathering and transport in WSN are discussed in this section. [33] outlines algorithms detailing the use of mobile sinks to collect sensor node data so as to prolong the lifetime of the node network. The main objective is to collect data at regular intervals from mobile nodes using a minimum amount of mobile sink. It also outlines a major drawback of using mobile sinks which is that they must be low in order to reliably gather information from

sensor nodes. This is a disadvantage since it may lead to significant data collecting delay from sensors that are at the end of the route which the mobile sensors are moving along. Information gathering must be done in a timely fashion since sensor nodes have a limited amount of memory. If their memory becomes full and they have no outlet to relay the information, then this causes a buffer overflow where new information or old information is disregarded.

Two approximation algorithms are generated to reach close to optimal results in a reasonable amount of time. These methods propose that mobile sinks visit positions of mobile nodes to collect their data. These algorithms are generalized so that the mobile sinks need only move within communication range of the mobile nodes to gather their data. The simulations conducted show an improvement over other algorithms which do not account for the communication boundary when determining the path planned for each mobile sink.

[26] deals with large scale WSNs that stretch across large geographic areas. These networks contain upwards of a thousand sensor nodes, which all need to be factored into an efficient data collection scheme. Approaches using mobile sinks and data collectors are both studied.

The first method uses mobile data collectors called MULE. This method will first partition the nodes of the network into clusters. The centroids of each cluster will house one mobile collector. The collector will utilize multi-hop routing. All the nodes in the cluster will relay their information from node to node until it reaches the mobile collector. Then collector will finally carry the data to a data sink and then return to its cluster. The second approach uses mobile data sinks which are categorized as aerial vehicles. The mobile sinks will path between the centroids of each cluster in a cycle. At each centroid it will broadcast a message to indicate

the initiation of data gathering. All the nodes of the cluster will receive the request and will directly use a single-hop approach to directly respond to the sink.

Both techniques were shown to have their advantages and disadvantages. The drawbacks which were highlighted when using mobile data collectors is that there may be a data "flooding" problem. This arises when the nodes that are closest to the collector must process the relay of information from nodes on the outer edge of the cluster. This leads to an increase in energy usage for these nodes which leads to quicker energy consumption and node failure. The second method also had a similar drawback, since in order for each node in the cluster to communicate with the mobile sink they must all use long range communication transmission. This is more taxing than short range transmissions, thus each node will slowly use more energy over time compared to using mobile collectors.

A common issue detailed in papers regarding WSNs and observed in the previous paper is energy consumption in WSNs. Recent work has also shown possible improvements for energy consumption. The work [34] is a recent paper which outlines a technique to use mobile nodes to lower energy costs. This tries to tackle the problem that data "flooding" has on nodes closest to data collectors or data sinks. Multi-hop relaying of information will wear out the nodes that must relay other nodes' information. Thus this paper hopes to use a node rotation strategy to circumvent this issue. The mobile nodes will take into account high power usage areas in the network and will rotate in and out of those parts of the networks periodically. This is a load sharing technique, where all of the nodes of the network will each have a turn being the closest or farthest from the data collection center. Simulations using this rotation strategy have shown an improvement in the lifetime of the network.

Data collection and energy efficiency both have seen recent improvements. Recent papers deal with real world conditions of mobile WSNs. Another area of interest is determining the optimal sensing radius for more favourable performance in WSNs. The paper [13], researches the effect of varying ranges of sensing radius'. A probabilistic method is used which takes into account the distance of an event to the mobile node and the "surrounding propagation environment" which basically means obstacles in the immediate proximity. This work uses this type of model for an intruder detection problem, where the detection time of the intruder is evaluated. This method shows that the actual results of detection time are slightly too high for other algorithms which do not take environmental obstacles into account for sensing capability. However, this paper also shows that a simple increase in the speed of movement by the mobile node can make up for this increase in detection time and can once again show comparable results to other approaches.

The last major area of work for WSNs discussed in recent times is on deployment strategies. The general strategies lie in either improving deployment strategies using mobile nodes or with self-deployment strategies from an initial static positioning. The paper [28] uses a variation on a Voronoi-based method using mobile nodes to develop a self deploying WSN in a finite unknown indoor environment. The method works by first sending two mobile nodes into the entry point. These nodes will determine the space layout of their immediate proximity and will broadcast the information to incoming mobile nodes. The following nodes will use the proposed Voronoi "Center-Mass" policy to move in the least number of time steps and account for collision avoidance. This method strives to have the Voronoi partitioning lines reflect as closely as possible with the sensing radius of each node to retain connectivity between nodes. The new broadcasted information to incoming nodes will be updated and subsequent nodes will

move into the new areas. This method allows for unknown indoor conditions to slowly be taken into consideration as the WSN deploys further into the environment. Simulation results show a higher coverage and lower total distance travelled by the mobile nodes over other algorithms.

## **2.5 Literature Review of Related Work**

In this section, we give an overview of papers that address the problem of coverage of a given area using WSNs. Several other approaches proposed and are relevant to this work will be presented and discussed. This section will outline the papers' work along with the advantages and shortcomings of each work.

The following paper [4] exhibits an approach to attain area coverage using sensor nodes. In this work, the authors hope to attain a  $k$ -coverage optima using WSNs.  $K$ -coverage means that at every scheduled time step, every location in the search space should be covered by  $k$  sensors and that those sensors are all connected.

This paper deals with algorithms mainly pertaining to the essential functionality of coverage and connectivity. Four different configuration protocols are propositioned to solve the  $k$ -coverage problem. The first is called "centralized randomized  $k$ -coverage," where the data center or sink is in charge of selecting the minimum number of sensors to guarantee  $k$ -coverage while maintaining connectivity. The second and third methods, called T and "D-clustered randomized connected  $k$ -coverage" respectively, utilize the sink and a subset of the sensors in clustered approach. The sink will select a group of sensors termed "cluster heads" which will select a cluster of neighboring sensors to  $k$ -cover and retain connectivity. Lastly is "Distributed randomized connected  $k$ -coverage," where all sensors are required to coordinate towards  $k$ -coverage. There is no global information sink in this last approach, as this distributed method will allow the nodes to have information pertaining to their neighboring nodes.



Even though this paper mainly studied the k-coverage problem, it still holds relevant data for an initial deployment scheme of static nodes. However, this falls short if environmental factors such as high wind or sudden hostile elements are put into play that may damage or move the static nodes. The static sensor nodes that are relocated or experience sudden failure will leave behind coverage holes. This highlights the reason why mobile nodes are imperative for optimal coverage.

[6] studies area coverage improvements using autonomous mobile nodes in the application field of intrusion detection. Intrusion detection is the concept of remote monitoring and event detection being used together to find an intruder. This is usually an application towards warding against unwanted elements entering an area of interest. The dynamic movement of sensor nodes is tested with respect to the coverage capabilities of WSNs so that an intruder may be detected quickly. With a limited number of sensor nodes, this paper hopes to reduce the detection time of a randomly located intruder using mobility measures. This research is practical for detecting intruders since they may bypass stationary nodes and thus the need for mobile nodes with the ability to dynamically search the space is increased. Initially the problem explored is of mobile nodes attempting to find mobile intruders. The performance metric is resolved as the time taken to locate an intruder.

The first approach used is to have initial random uniform deployment of mobile nodes. These mobile nodes will also have an assumed random direction of movement at the first time step. Varying movement speeds were utilized to determine the pace at which a mobile node could move which would not be detrimental to its sensing capabilities. At higher movement speeds, the mobile node will cover more area more quickly. However, each mobile node has a

baseline sensing time requirement which means that it must still move slow enough to account for its sensors to gather information and act upon that knowledge.

In order to study the optimal strategy to be used by the intruders and the static and mobile sensors, the authors offered a game theoretic approach. The game theory decision makers are the mobile nodes and the intruders. This paper details a "zero-sum mini-max game" which is one in which each decision makers' losses and gains are equally balanced. However, even though this approach worked well to move mobile nodes to detect intruders, the approach lacked any concrete full coverage scheme.

An approach towards maximizing the area coverage by mobile nodes with regards to collaborative event detection was introduced in 2007 by Lambrou et al. in their paper [2]. These authors coordinated a collaborative architecture in which mobile nodes would sample the areas which are least covered by the initial deployment of static nodes. Static sensor nodes which are alerted to a possible event occurrence may report this information to mobile nodes in the vicinity so that they may inspect the given area and validate whether an event occurred. The mobile nodes autonomously choose which route to take based on local information and any reports from stationary nodes nearby.

This paper proposes an algorithm which not only attempts to reliably detect events in uncovered areas, but also uses mobile nodes to traverse these gaps to verify events in such a way that the areas with the lowest coverage are sampled first. This means that the areas with the largest gaps or holes will have a higher chance of a mobile node moving towards that direction. In order to achieve this, different algorithms are proposed including the Grid Scan or One Scan algorithm, the Zoom algorithm and a path planning algorithm. For each of these methods, the

mobile nodes must know where the other mobile nodes and static nodes are so as to avoid collisions when planning their paths.

The first algorithm introduced is the Grid Scan to update information on uncovered cells for each of the mobile and static nodes. The One Scan algorithm is also used as another way to locate coverage holes and is an improvement of performance to the Grid Scan algorithm.

In order to improve performance further, the zoom algorithm is introduced which is a divide and conquer approach. The resultant solution is a ranking of the uncovered holes from largest to smallest. Mobile nodes are placed in the holes ranked largest. Once the holes are found then a path planning approach is utilized to move the mobile nodes towards other holes.

Using the above mentioned algorithms, experiments were conducted in this paper on an initial coverage after initial deployment of mobile and static nodes and another on the path planning method. The path planning approach was conducted in a 300 square meter area with 100 static nodes and a sensing radius of 10 meters. This experiment was mainly conducted to find one event in the target area, thus total area coverage is not tested here. A possible approach to test the total area coverage using this path planning approach could be to have multiple different events evenly spread out in the search space. This would force the approach to try to maximize the area coverage while also choosing its path wisely when moving towards all the events.

This paper's importance lies in that it is one of the first to use the divide and conquer zoom algorithm and a combination of it in a path planning approach for WSN area coverage. While a fast scheme to path mobile nodes towards coverage holes is a good approach, it still falls short in terms of total coverage in the search space.

A paper with a similar premise to the above mentioned paper is [11] by the same authors Lambrou, et al. two years later. The idea put forth in this paper is to use similar algorithms as used before, however, instead of specifically dealing with the detection of an event, the authors now try to improve overall area coverage in sparse WSNs.

The algorithm proposed is one that utilizes the Zoom algorithm followed by an autonomous aspect in the mobile nodes. The premise still lies in collaborating stationary and mobile node information. First, the Zoom algorithm is used to determine the rank of the coverage holes from largest to smallest. The mobile nodes are placed within the largest ranked uncovered areas first and determine a direction to move towards their next closest coverage hole. The mobile nodes will query neighbouring nodes within their communication range. Once the proximal node positions is known, the information of the mobile node position, direction of movement and destination will be shared with the neighbouring nodes. Thus both of the mobile nodes which are communicating will update their movement information if both of their paths will cross. Otherwise, the mobile nodes will autonomously navigate through the sensor field. This autonomous movement will take into account the other nodes' sensing radius and any coverage holes found and will attempt to pass in such a way to improve area coverage while moving towards the destination area.

This distributed and dynamic approach is simulated on a 100 by 80 meter grid. Each sensor node's sensing radius is 2 meters and their communication range is 10 meters. The initial deployment will introduce 100 randomly placed static sensor nodes. There were multiple experiments conducted to determine the coverage improvements of the proposed path planning approach against standard deterministic path planning approaches. The deterministic standard method will move mobile nodes back and forth while keeping sensing radius into account so as

to not overlap on areas which were already covered. An example of this strategy is shown in Figure 1.

The first experiment utilizes 1 to 3 mobile nodes. In each case the coverage reached about 94% after being given sufficient time. The second involves testing the path planning approach against a deterministic path planning and random path planning approach. In this experiment with 1 mobile node over 1000 iterations reaches 90% coverage. The last experiment involves an average coverage accomplished over 100 random deployments with 2 mobile nodes. The results show an average coverage of 85% after 500 iterations.

As indicated above, the proposed algorithm improves area coverage compared to deterministic and random path planning algorithms. Using mobile nodes to sample regions not covered by stationary sensor nodes autonomously is an important task. This is due to the fact that this type of approach is essential for very large areas using a distributed WSN. The downsides of the path planning approach and the deterministic approach are that they both lead to already covered areas. The path planning approach seems to have a tendency to move back over areas already sampled which is inefficient and wastes time.

Another paper written by Lambrou, Theofanis P., and Christos G. Panayiotou, [9], describes a similar approach to the previous two papers. This paper designs a collaborative architecture in which mobile nodes use information about their local environment along with the Zoom algorithm to determine a path to a coverage hole. The significant components of the path planning approach are a neighboring sensor collaboration and a target cost function regarding destination information for mobile nodes.

The algorithm premise is a path planning method based on the "receding horizon" approach. The "cognitive map" is generated which holds possible future movement positions for

each mobile node. The mobile node chooses the candidate position that achieves the minimum cost, where cost is based on movement into already covered areas. The mobile nodes are allowed to either have pre-specified destinations or have a dynamic nature with short and long-term goals. The static nodes check whether an event has transpired and will broadcast this to mobile nodes, so that they may check. Specifically, the algorithms proposed uses the Zoom algorithm, source position estimation scheme and distributed target allocation to query nearby mobile nodes for area coverage collision detection and prevention.

There were multiple simulations performed using varying number of mobile nodes, different suspicion thresholds and with different path planning approaches. The experiments were performed on a 300 square meter grid, with 100 randomly deployed stationary nodes, the mobile movement set to 2 meters and a sensing radius of 10 meters. The first experiment which will be mentioned is one to demonstrate the "Distributed TS algorithms" behavior. This algorithm is combination of multiple factors mentioned in this paper. A cost function, a target position method and coverage hole detection algorithm are all implemented in this approach. The suspicion threshold is changed to determine how many event are detected, alongside the area coverage improvement. The results after 1000 iterations showed that the best configuration resulted in all events being found and a coverage of about 83%. The last experiment is a comparison between Distributed TS algorithm and other path planning algorithms. One of the approaches is a search mission method which uses no target destination information. The other two are similar in that they both use a central controller to determine the next step of a mobile node. When comparing to this paper's algorithm, they all fell short in terms of coverage improvement. Distributed TS algorithm achieved an average of 88% coverage which is almost 5% higher than the other three.

This paper has chosen to attempt to combine different approaches together to handle multiple different situations, however, the results ended up slightly lower than the previous methods' performance for their specific determined tasks. The same problem of the mobile nodes having a chance of moving in a loop lies in this approach as well.

The next paper discussed is [10]. This paper uses static and mobile nodes together dynamically, through a bidding approach, to maximize area coverage and event detection. The mobile nodes will only sample from static nodes within their communication range. Two different bidding protocols are implemented to utilize static node information to direct mobile node movement towards holes which will increase coverage. The two protocols are a basic bidding protocol and a proxy-based bidding protocol.

The first basic protocol is a greedy heuristic approach for an NP-hard problem. It utilizes Voronoi diagrams from the static node positions to find the largest holes. Thus, when an event transpires, the sensor node closest to it should detect the event happening if the event transpired within its Voronoi diagram cell. Each static sensor node need only check its own cell for event detection. If the cell surrounding a sensor node is too large and an event cannot be detected by the sensor node, then the event must have transpired within a coverage hole. The static nodes will utilize their information gained from the Voronoi diagram to then broadcast a bid for a mobile node to come fill an adjacent hole. The broadcast will include information on how large the hole is so that the larger holes will be filled first. The mobile nodes compile their local static node information and accept the highest bid by a static node. Finally, the mobile node will move towards the coverage hole near the static node.

The second protocol introduced is the proxy-based bidding protocol. This protocol acts similarly to the basic bidding protocol since they both utilize static node information gained

through Voronoi diagrams. However, there is a clear difference between the two as the proxy-based approach does not automatically move the mobile nodes towards the largest coverage hole found. Instead, the algorithm will allow for "virtual" moves to be considered similarly to the Receding Horizon algorithm. These virtual moves are implemented such that the path of the mobile node is determined before it starts moving. The mobile node path is setup so that it will move from smaller holes towards the larger destination hole. This is all done through message passing before any movement occurs. Finally, once the path is found, then the physical movement takes place. This protocol is an improvement since movement of mobile nodes is more expensive than message passing [10].

The experiments conducted in this paper are on a 60 square meter field with 60 sensors and a sensing range of 6 meters. The amount of mobile nodes is set as a percentage from 10 to 50 percent of the total sensor nodes. The results found were that with 10% mobile nodes or 6 mobile nodes, the algorithm attained a 90 percent coverage scheme. As the percentage of mobile nodes increases, the coverage increases, with 20% mobile nodes yielding 94% coverage and 50% mobile nodes yielding 98% coverage. The increase of mobile nodes also led to lower energy consumption, however, it led to higher message complexity and a higher average sensor cost. This paper proposed a bidding protocol to guide the movement of mobile nodes towards coverage holes, so as to balance sensor coverage with cost. The mobile nodes are treated as servers which aim to "heal" coverage holes which is an interesting approach. The main importance of this paper is the use of a bidding protocol which increased coverage and utilized local information for large scale movements. This paper also fixes the issue from the previous one where only one event was tracked. In this paper, the goal is to cover as many holes as possible using mobile nodes.



From the paper titled [1], there is a similar approach using a bidding strategy. The starting scenario is constant in that there is a set of static sensor nodes which are randomly deployed in the search space along with a smaller subset of mobile nodes. The static node infrastructure will estimate coverage hole locations and furthermore help in navigating mobile sensor nodes towards these coverage holes. The strategy used to guide the mobile nodes is a bidding strategy.

The bidding strategy that is described in this paper is tweaked differently than the previous one. In this algorithm, the mobile node will actively try to navigate towards a coverage hole. Whenever a mobile node begins to decide upon its next destination it will broadcast an "auction message" and will then wait a set amount of time. Any static node within the communication range of the mobile node will be able to receive this message. Any static node that is able to, will estimate the location of the largest coverage hole in its vicinity. This is done by executing the Zoom algorithm only on their local area. Once each static node has the information regarding its largest hole, they will each communicate back to the mobile node a "bid" with the data pertaining to their proximal coverage hole size. After the designated auction time, the auction closes and the mobile node chooses the highest bidder and moves towards that coverage hole. Should the bidding strategy fail, such as when there is no static nodes in range or all the local area surrounding the neighboring static nodes is already covered, then the mobile node will retain some autonomous action. In this case, the autonomous action is to use the Zoom algorithm to estimate a global coverage status and then move towards the largest hole found globally. This is termed a "coordination algorithm."

The simulations of the bidding approach were carried out on a 300 square meter region. The number of randomly deployed static nodes varied between 0 and 200 and the mobile nodes

varied between 1 and 5. The sensing radius was set to 8 meters and manoeuvrability was set to 2 meters. In the first experiment the iterations needed to reach 95% coverage with varying static and mobile node combinations is shown. The general results show that as the number of static nodes increases, there is a gradual decrease in the number of iterations needed. Similarly, using more mobile nodes would also decrease the iterations needed, with the largest gap being from one mobile node to two mobile nodes, where the iterations were essentially halved from 3500-8000 iterations with one mobile node to around 2000-4000 with two mobile nodes. In the next simulations worked with optimizing coverage based on iterations passed. The coverage was able to reach close to 100% when enough iterations are given, which is above around 4500 iterations in the worst case and up until 1500 iterations in the best case.

The goal of this paper's work is to improve sensing area coverage of WSN through use of a distributed path-planning approach. The method proposed is a bidding strategy which shows good results in terms of total coverage improvement and time steps taken to reach a coverage percent. The results showed promise, however, at the cost of increasing the number of static and mobile nodes.

The next paper to be discussed is [7]. This paper, attempts the same type of process as other papers which use stationary nodes to aid mobile nodes in their movement decisions. However, the way in which the coverage holes or "blind zones" are found, and the information being relayed is different in this paper.

Due to the fact that WSNs are usually composed of a large number of sensor nodes in less than favourable conditions, the ability to keep all the nodes operational is limited. With little chance to replace or fix nodes which have either broken or run out of energy, the performance of

the network weighs more heavily on mobile node coverage in areas with poorer conditions. Coverage, in this paper, is a measure that reduces "blind zones and redundant coverage".

Multiple different parameters are implemented into a new deployment and movement strategy. To combat redundancy in deployment, the sensors nodes are allowed to alter their active state to a sleep status. This will reduce redundancy and allow the WSN to extend its lifetime since the nodes can alternate between sleep and active states. The actual movement algorithm implemented lies in calculating the Euclidean distance between neighboring the sensor nodes within communication range. Taking into account the sensing radius of each sensor node, the nodes which are apart a distance greater than twice their sensing radius may have a coverage hole in between them. When calculating based on neighboring nodes, if the middle point between any of these Euclidean distances lies within the sensing radius of a nearby node then there is no coverage hole. If the point does not lie within any sensing radius, then there is a blind zone. The mobile nodes will be placed within these coverage holes found and will path towards other such blind zones.

Various simulations were done on a 100 square meter area with 80 randomly deployed static nodes. The sensing radius is varied between 5 and 20 meters. The algorithm is run for 6000 iterations, during which the coverage percent reaches a maximum of around 92% at around 4500 iterations.

These results of over 90% coverage are good, however, it seems that the algorithm takes longer than those previously to reach such a percentage. This algorithm first tried to repair blind zones and only second did it try to optimize overall coverage. Although the results are slightly lesser than in other papers, the approach used is different and innovative.

The next paper highlighted is [14]. This paper introduces an innovative approach to area coverage as it handles the problem of mobile sensor node deployment in an unfamiliar environment. This environment space can be any area in which there is no previous knowledge of the size, layout or conditions. A "potential-field" approach is used in order to improve uniform area coverage of the unknown space.

The algorithm put forward is one in which the manoeuvrability of mobile nodes and their ability to sensing not only their environment but also other neighboring nodes is highlighted. This algorithm strives to utilize only mobile nodes and no static nodes, and allow the mobile nodes to "self-deploy." This entails starting from a compact initial setup and then spreading out within the search space so as to maximize area coverage. The way this is implemented is through the use of the concept of potential fields. This basically means nodes which are closer together will move away from each other while still keeping a favourable distance with regards to their sensing capabilities. Each node will be repelled when it is near obstacles or other nodes and be forced to move away. This will allow the initial mobile nodes to distribute themselves with low redundant area coverage. There is also a "friction force" added, which will slow the mobile node movement quickly to a halt. This will allow them to react to other nodes movement towards them while also not moving so far away that holes will be formed. Furthermore, their movement will slow to a halt which will allow for a final static deployment. This approach is scalable to any area in which it is used and will allow the nodes to spread themselves more evenly throughout the search space.

The experiment conducted was on an unexplored layout of a building 700 square meters large. Starting from an initial deployment of mobile nodes in a 50 square meter area, the nodes were able to move in such a way that they covered above 500 square meters of area. When the

mobile nodes finish in their static positions, the coverage attained may not be optimal in terms of the whole grid. However, the areas which are covered have almost no redundant sensing between nodes and are covered regardless of the obstacles.

The paper specifically states that the algorithm used above does not specifically deal with coverage. Coverage of the network emerges as the mobile nodes find their optimal positions. From the start to the end, this approach seems more like a smart deployment strategy rather than any path planning or coverage approach. However, beyond these factors, the approach can be an innovative way of thinking for how to solve the coverage problem and shows good results in doing so.

The final work which will be discussed is [25]. The issue these authors are tackling is to reduce energy usage in the sensor network through the placement of mobile base stations. Although this paper does not specifically deal with the mobility of mobile nodes to fill coverage holes, it does take into account mobility of nodes and the aspect of locating an optimal position to move these mobile nodes at each time step. This is quite similar to our research in that both methods are trying to find an optimal movement path for mobile nodes. The only different is the purpose for which this is being done.

This paper deals with moving the base station in an optimal manner. It is established that the one-hop neighbors of the base station are using much more energy than other nodes. By moving the base station, the one-hop neighbors change and the load is spread across various nodes. The algorithm put forward is an integer linear formulation (ILP) approach to verify new locations for the mobile base station. "Feasible sites" are found through the ILP and the mobile base station moves towards the most feasible one.

This is similar to our approach which uses an ILP to verify an optimal path for the mobile nodes so that they may optimize area coverage. Although the performance parameter is different, the method being used is quite similar. Thus since this paper has shown improvements in energy cost reduction, we hope that a similar approach using a MILP formulation will lead to improvements in area coverage.

# CHAPTER 3

## Thesis Contribution

The third chapter of this thesis introduces the contributions of this thesis, namely the two proposed MILP formulations. The objective of these MILP formulations is to maximize area coverage by using mobile node movement through a WSN. By optimizing area coverage, the amount of undetected events in the field of reference is minimized. By solving these MILP formulations, the impact of uncovered areas from a WSN is lessened.

In the following section, the information regarding the performance measures, the network and field models are discussed to give a better understanding of the proposed approaches. Afterwards, both MILP formulations are presented with a detailed description of the objective function and a set of constraint equations. The two approaches aid in different situations of testing which will be discussed after each MILP is introduced.

### 3.1 Outline of our proposed approach

The important aspects of our WSN architecture are displayed in Figure 4 and outlined in the following section.

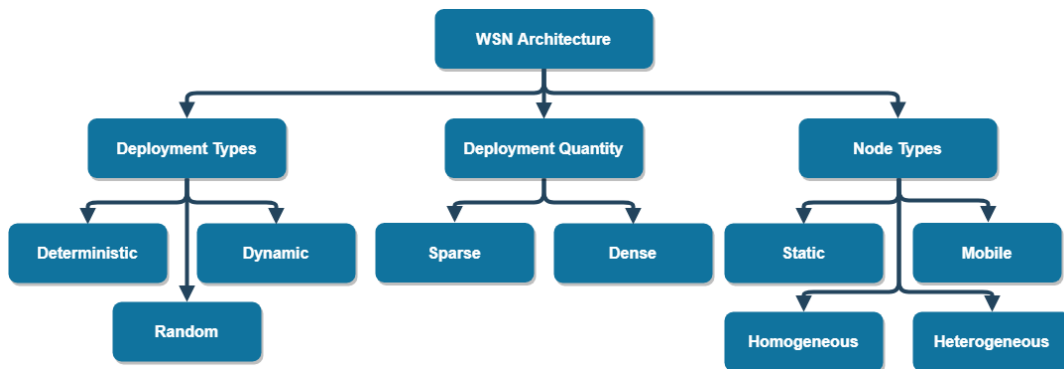
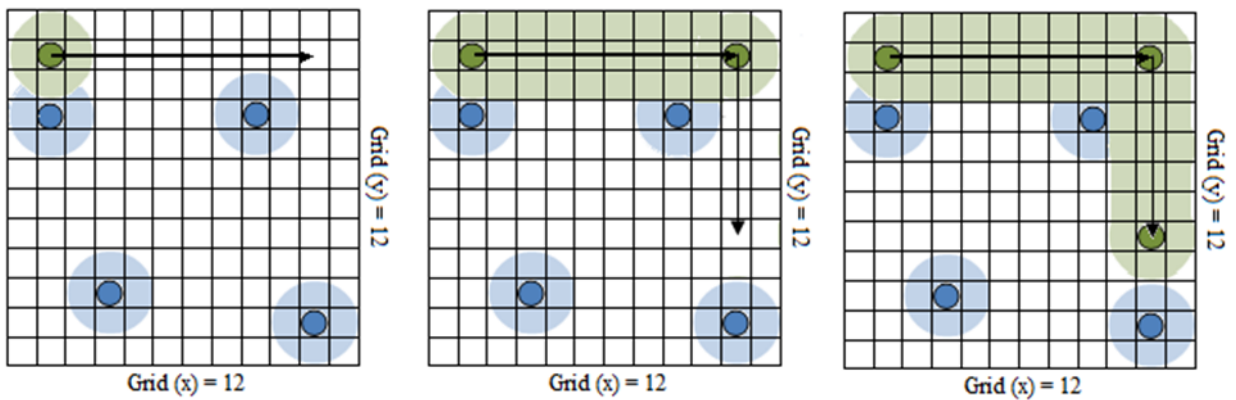


Figure 4. WSN Architecture Components

A traditional WSN architecture is primarily assumed to be a dense network consisting of a large number of sensor nodes that reliably cover and monitor a large area where any of the sensor nodes can communicate amongst one another through multi-hop communication paths. Consequently, these dense networks also assume the use of static sensor nodes with no manoeuvrability. This approach of spreading many nodes to cover large areas is impractical. Firstly, the addition of an increasing number of nodes leads to a prohibitive cost, not only monetary but also in other factors such as steeper deployment, management and maintenance costs as well as leading to the possibility of redundant nodes with overlapping sensing radius'.

In this thesis, we introduce a deterministic approach to finding an optimal path that the mobile nodes should take in order to attain optimal coverage while also doing so in the least number of iterations. Instead of trying to optimize a static sensor node deployment scheme, this thesis is concerned with the optimization of the movement capabilities of mobile nodes. Thus a small amount of mobile nodes with controllable movement are used in lieu of more static nodes. Specifically, the maximization of area coverage is targeted by locating the optimal locations each mobile nodes should move through at each time step. Figure 5 displays a sample route planned for the mobile node over 15 time steps. The mobile node moves around the static nodes to reach uncovered holes in the search space.



**Figure 5. Progression of Movement of Mobile Node over 15 Iterations**



### 3.1.1 Novel and Innovative Features

Two different coverage measures are used as an objective for the path planning approach submitted in this thesis. These include area coverage and time interval area coverage. Area coverage is the measure of the amount of the search space which is within the sensing radius of one or more sensor nodes. The search space is segmented into a grid, thus area coverage is determined based on which grid points are covered at a given time. This thesis hopes to optimize the area coverage by using a mixed integer linear (MILP) formulation to guide mobile nodes along an optimal route through uncovered zones.

Similarly, the time interval area coverage is the area of the search space covered over a set period of time. In this thesis, another MILP formulation is created to optimize the area coverage and also to do so within an optimal amount of time steps. Thus the time interval is being optimized so that the optimal route for each mobile node is chosen. These coverage measures depend on the static and mobile node properties together. Whereas the area coverage is an important measure to optimize, the time interval in which the area is totally covered is also important for applications that cannot afford to fully cover the search space by static nodes. Mobile nodes allow for improvements in area coverage over time.

Specifically, a Mixed Integer Linear Programming Formulation was used as the deterministic path planning approach for this thesis. Throughout other papers reviewed in the literature review, an MILP is only implemented to discover coverage holes in the search space of a WSN. This thesis uses a MILP as a path planning method which is an innovative feature that differs from existing approaches.

## **3.2 In Depth Description of Approach**

### **3.2.1 Contribution**

The main contribution of this thesis is the investigation of path planning approaches and the subsequent planning of routes for mobile nodes to take for certain objectives. The specific aim of this thesis is the development of a path planning technique using mobile nodes for the improvement or maximization of area coverage. This method will be used on both a sparse and dense WSN with stationary sensor nodes and mobile nodes. The algorithm is a deterministic approach using coverage hole coordinates and static node information. Once the information is fed back to the mobile sensor node, it will determine an optimal path through each coverage hole. It will also try to avoid passing over already covered regions in the path planning phase. The aim of this technique is to improve area coverage of the network to an optimal level. An approach to do so in the minimum amount of time is also proposed. Specifically, the contribution is to:

1) Develop a path planning protocol to achieve 1-degree coverage over a set period of time using WSN with mobile nodes. At any one point in time the coverage degree is less than one. However, when the path of the mobile nodes are taken into account, the overall degree coverage from the time it takes the mobile nodes to traverse its complete path should be 1-degree coverage.

### **3.2.2 Importance of Area Coverage**

Coverage of a search space using WSNs is an important measure of whether the sensor nodes allow for timely access to environmental information and for adequate monitoring of the field. It is a measure of the surveillance quality of the WSN for the field of reference. This thesis similarly uses coverage as the performance measure of a field using WSNs [29].

Coverage is the main performance measure used in various applications such as event detection. Many pieces of literature highlight applications dealing with intruder detection and try

to maximize coverage so as to decrease detection times. The intruder is usually a biological agent that is being tracked, however, this is not true in all cases. Many cases define chemical, radiation and other factors that are tracked as if intruders in a search space. Thus, the importance of area coverage is more wide spread and useful to almost any application field [2][6][9].

There are various types of coverage which are studied in literature and applied towards real world problems. A basic deployment coverage is one such strategy which is used to arrange sensor nodes into appropriate locations so that the search space is totally covered within the sensing radius' of the sensor nodes. However, a continuous full coverage is infeasible realistically for large areas due to increased cost as outlined in Chapter 2. Thus a continuous partial coverage scheme is contributed as a path planning approach. Using mobile nodes, areas can be left uncovered at initial deployment time. The mobile nodes can then be moved to fill the areas which have been left open so that full coverage can be reached over time. This will allow some areas to be covered and uncovered at different periods of time which will reduce monitoring time in those areas, but will relieve the network to be more feasible and reliable when component failure occurs [6][29].

The path planning approach proposed in this thesis is mainly used for a partial coverage deployment strategy with the aid of mobile nodes. The approach can be utilized for partial blanket coverage, barrier coverage and sweep or point coverage problems [29][35]. Since the mobile nodes are able to move about in the field of reference, a partial blanket coverage scheme can be fulfilled by having mobile nodes move through areas that are uncovered in a cyclical route [9]. Thus each location will be covered by a sensor node within the time it takes for a mobile node to complete an entire cycle of its planned path from a set beginning point [29].

### 3.2.3 Importance of Mobile Nodes

The introduction of mobility through mobile nodes in WSNs is beneficial for multiple different reasons such as for connectivity, cost lowering, reliability, energy efficiency and area coverage. For a dense WSN with many nodes, connectivity is usually not a large issue, since the nodes are closely packed together and are able to communicate with multiple other nodes. The difficulty lies in sparse WSN where static nodes cannot cope with isolated regions or large coverage holes. A sparse WSN architecture becomes much more feasible when mobility is added to sensor nodes. Furthermore, with the addition of mobility, fewer stationary nodes are necessary to cover areas in which mobile nodes may route through. Thus less sensor nodes are needed which decreases the cost. Even though the addition of mobility to a node increases the cost of those individual mobile nodes, a WSN which uses mostly static nodes and a few mobile nodes to fill in the imperfect coverage areas is a key strategy to lower cost and improving performance.

Mobility is similarly important for improving reliability and energy consumption in WSNs. The use of very dense WSNs leads to many different problems such as increased energy consumption. The communication methods used in WSNs is usually multi-hop communication, where the node will relay their information along other nodes in a route towards the data collection center. This leads to problems with the nodes which are directly beside the data center, since they will be constantly in use for routing which will increase their energy consumption drastically. Furthermore, the longer the message must travel along a multi-hop connection, the higher the chance of message loss occurring, if a node is unable to complete the transfer of information at any given time. Thus mobility is introduced in many different ways to counteract these problems. For energy conservation, a possible strategy could be allowing the closest node to a data center to move away while rotating new nodes into that position will decrease the strain

on any singular nodes energy reserve. For reliability, allowing specific mobile collector nodes to collect data from the nodes will reduce the risk of message loss along long routes since the mobile collector node can move freely throughout the search space. These are examples of ways in which mobility is able to reduce the impact of different problems found when using WSNs.

While mobility is very useful for WSNs, it does have some detriments as well. These are mainly new problems which must be accounted for when using mobile nodes. Firstly, the mobile nodes movement pattern must be clearly defined. They must be controlled in such a way that redundant movement is minimized and a performance measure is maximized. Furthermore, since communication between nodes can only be conducted within transmission range, mobile nodes must define an efficient amount of time to stay stationary at certain times so as to allow for reliable communication between nodes. Even with these new issues, mobility is still a driving force in reducing pre-existing problems with WSNs [3].

### **3.2.4 Types of Mobility**

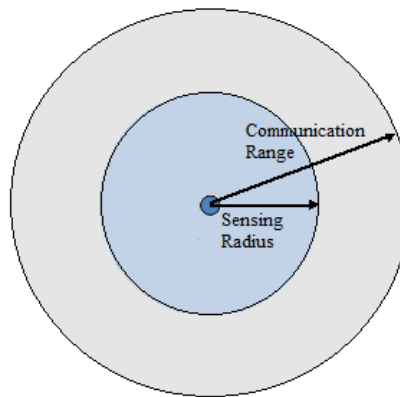
Varying types of mobility may be used for mobile nodes in WSN depending on the situation at hand. Whether more controllability is necessary or a more autonomous method is needed, mobility has various uses in different application fields. The different types of mobility are deterministic, dynamic and random as displayed in Figure 4 at the beginning of this chapter. The first type is deterministic which is a method of using mobility to guide mobile nodes along a predefined route. This can be characterized as movement on a scheduled path, where the mobile nodes regularly pass through specific points within a given interval of time. On the other hand dynamic movement is the ability of mobile nodes to change their location on demand. This is more flexible to changes in the environment but more difficult to implement. Usually, dynamic movement of mobile nodes requires additional processing of environmental conditions through

each mobile node. In many cases, the mobile nodes must find out their position relative to their surroundings in order to circumvent obstacles and move towards an objective space. The communication between the mobile nodes and their neighboring nodes is a vital characteristic in dynamic approaches which may lead to more issues to consider with constant transmission of information. The last type of mobility is random movement. This is relatively self explanatory in that the mobile nodes have a probability of choosing where to go. This method is relatively unstable since contact between nodes is on irregular intervals and difficult to plan around [3].

### 3.2.5 Assumptions

This next section summarizes the assumptions upheld during the modeling and path planning phases. Definitions of concepts such as the underlying information structure of WSNs and their impact on the thesis' objectives are outlined.

The first assumption is that the sensor field area is a rectangle of dimensions  $x$  by  $y$ . The sensor nodes of the WSN which will be placed in the search space are all assumed to have the ability to know their current location by dimensions in the sensor field area. Furthermore, each mobile and static sensor node will have a common sensing range ( $r_s$ ) and a common communication range ( $r_c$ ) such that  $r_c > r_s$  as exhibited in Figure 6.



**Figure 6. Sample Sensing and Communication Range of a Sensor Node**

The property of identical sensing and communication ranges for each sensor node is termed homogenous sensor nodes. The sensing range of each nodes is set as a circle surrounding the coordinate point the node is stationed on with the radius of the circle equal to its sensing radius. Furthermore, it is assumed that each node has a reliable communication link to other sensors that are as far away as their communication radius allows them to communicate.

An assumption made for the WSN used is that all sensor nodes are able to communicate to the data sink or data center through multi-hop routing. Thus the nodes are allowed to communicate information which they sense along a pre-determined multi-hop route to the data collection point. The way in which this is accomplished is not a major facet of this thesis' work.

This thesis also includes the assumption that the environment is relatively static. This means that any component that is set as "on" or working at the start of the simulation is assumed to stay that way for the duration of the experiment. In the case of more dynamic environmental conditions where the sensor nodes are allowed to enter a "sleep" cycle are generally not considered for this approach.

### **3.2.6 Physical and Network Model**

In this section, we describe the underlying network architecture and relevant terminology being used to refer to network parameters. The WSN architecture used includes sensor nodes for data collection and data sinks for data storage. The sensor nodes are used as the source of information gathering since they sense environmental changes and relay that information through the network. These sensor nodes may either be stationary or relocatable mobile nodes. The mobile nodes are mainly used for coverage purposes, since they are able to move through areas in the search space which are uncovered. The data sinks or base stations are the final destination

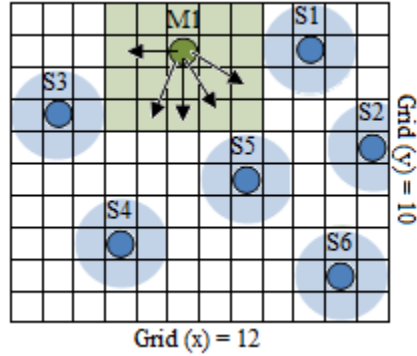
point for the information in the WSN. The sinks will collect the data from the sensor nodes and then store it for future processing.

This thesis uses a search space that is a rectangular grid divided into congruent squares with the total area of the region being  $x$  by  $y$ . Each congruent square is denoted a cell and can be accessed based on its index in the grid. This index is the  $(x, y)$  coordinate dimensions of the grid, and the overall dimensions of the grid are the real world dimensions of the land space that is being covered by the WSN.

This thesis considers a set of nodes  $|N|$  with  $|S|$  stationary sensor nodes and similarly a subset of mobile sensor nodes denoted  $|M|$  such that  $|N| = |S| \cup |M|$ . The static sensor nodes are randomly placed in a two dimensional rectangular  $x$  by  $y$  field at positions  $(i,j)$  where  $i$  is the position of  $x$  coordinate and  $j$  is for the  $y$  coordinate. This position's coordinate is constrained between  $1 \leq i \leq x$  and  $1 \leq j \leq y$ . The mobile nodes will be categorized as variables denoted  $(xkij)$ . The variables  $i$  and  $j$  both have the same meaning as in static nodes while  $k$  is the time step in which the mobile node is positioned at coordinate  $(i,j)$ . During the first iterations for the route of the mobile node, the  $(xkij)$  value of  $(x0ij)$  will be set to the initial location of the mobile node. This is usually set as a random position of  $(i, j)$  since the initial deployment usually consists of a random deployment. There are some instances where the full grid will be partitioned into subsections and the MILP approach will be calculated for each subsection. In these cases, the mobile node will move from one subsection of the grid to another and the initial position of the mobile node will be set to the coordinate location of the entrance position of the mobile node with respect to the subsection. There is a base assumption that all the sensors know their coordinate locations through a GPS tracking method or through a localization technique. In



terms of the mobile nodes, each one will have a grid field map of the search space similar to the example representation in Figure 7.



**Figure 7. Example of Field Grid Map**

Figure 7 displays an example of a Field map that a mobile node would have. In this diagram of a 12 by 10 grid, there are six sensor nodes denoted S1 to S6 that are located at coordinates (10, 2), (12, 5), (2, 4), (4, 8), (8, 6) and (11, 9) respectively and one mobile node at coordinate (6, 2). Around each static node is a circular shaded area denoted a neighbourhood of cells. A neighbourhood of cells is defined as all cells that are less than or equal to the distance of the sensing radius away from the coordinates origin ( i, j). In this diagram, the sensing radius is set to one. Furthermore, the shaded area surrounding the mobile node indicates the potential locations it may move to in the next time step within its movement ability of 2 units per time step.

A sensor node is reported to be able to reliably detect events or environmental changes within a circular region around itself. This region is contained within a circular region of radius equal to the sensing radius ( $r_s$ ) of the sensor node. For the research in this thesis, it is assumed that if an event transpires within the sensing radius of at least one sensor node, then the event is determined as detected by the network as outlined in Figure 8.

$$\text{Probability of Sensing an Event} = \begin{cases} 1 & : \text{When target is within Sensing Radius} \\ 0 & : \text{When target outside of Sensing Radius} \end{cases}$$

**Figure 8. Sensing Capability of a Sensor Node**

It can be pointed out that at some points in time the mobile nodes will have a slightly inaccurate outlook on the state of the grid and the sensor nodes within. One main facet of this approach is that the mobile node's mapped information can be updated at given intervals as the mobile node moves through the search space. Thus if the central controller or data center discovers a change such as a malfunctioning sensor node, it may update the grid information for the mobile nodes. This can be performed by adding the mobile node's current location to the information it receives and then performing the path planning approach.

### **3.3 MILP Formulation Approach**

The approach used for determining the optimal path for each mobile node to maximize area coverage is a Mixed Integer Linear Programming formulation. A MILP is a set of mathematical equations that each represent a different characteristic of a given problem. The equations are split up into objective function, constraint equations and variable declarations. The variables used are a mixture between integer and binary variables. Integers are set as whole numbers and binaries are set as numbers that can be either one or zero. The objective function is the equation which is being optimized. This function is optimized to find the optimal maximum or minimum value possible for the objective. In order to be certain that the objective function reliably reaches an optimal value, constraint equations are set into place. These equations constrain the objective value such that they follow the set of restrictions set in place for the given application. An example of a constraint is to set the upper bound on the movement of a mobile node. This will constrain the objective function to reach an optimal value such that it must only move mobile nodes a specific distance at each time step. The final restriction for a MILP is that each equation must be a linear equation. Thus each parameter can only have a degree of one, which restricts from using other functions such as quadratic functions.

### 3.3.1 MILP - Coverage

The first path finding MILP formulation proposed is termed MILP-Coverage. It is an approach to find the optimal area coverage within a set number of allowed time steps. The formulation for coverage of WSN and its components are outlined below.

#### MILP-C (MILP-Coverage)

##### Set of Variables

$S^1$  = set of cells not covered by static nodes;

$S^2$  = set of cells covered by static nodes;

$S$  = set of all cells =  $S^1 \cup S^2$

$p_{i,j} = 1$  if there is static node at cell (i, j)

$r_s$  = sensing radius of a node (in terms of number of cells)

$(i, j) \in S^2$  if  $(m, n)$  s.t.  $p(m, n) = 1$  &  $|m - i| \leq r_s$  &  $|n - j| \leq r_s$ .

$\rho_x (\rho_y)$  = maximum number of cells mobile node can travel in x (y) direction in 1 iteration.

$K_{max}$  = maximum number of iterations possible.

##### MILP Variable Listing

Binary variables:

$x_{i,j}^k = 1$  if mobile node is located in cell (i, j) during iteration k.

Continuous variables:

$c_{i,j} = 1$  if cell (i, j) covered by mobile node at least once during all intervals.  $0 \leq c_{i,j} \leq 1$

##### Objective Function

MAX  $\sum_{i,j \in S^1} c_{i,j}$

##### Constraint Functions

Subject to :

##### Position constraint

$$\sum_{(i,j)} x_{i,j}^k = 1 \quad \forall k = 1, 2, 3 \dots K_{max} \quad (1a)$$

$$\sum_{(i,j)} x_{i,j}^0 = 1 \quad (1b)$$

##### Mobility constraint

$$x_{i,j}^{k+1} \leq \sum_m \sum_n x_{i+m, j+n}^k - \rho_x \leq m \leq \rho_x, -\rho_y \leq n \leq \rho_y, \quad \forall k = 1, 2, 3 \dots (K_{max} - 1) \quad (2)$$

### Cell coverage constraint

$$c_{i,j} \leq \sum_{m=-r_s}^{r_s} \sum_{n=-r_s}^{r_s} x_{i+m, j+n}^k \quad \forall i, j \in S^1, \forall k = 1, 2, 3 \dots K_{max} \quad (3a)$$

$$c_{i,j} \geq 0, \forall i, j \in S^1 \quad (3b)$$

$$c_{i,j} \leq 1, \forall i, j \in S^1 \quad (3c)$$

### Justification of the MILP:

The objective function of MILP-Coverage maximizes the total area coverage ( $c_{i,j}$ ) over all grid spaces over all time steps. The values of  $c_{i,j}$  are combined to form the total area coverage for the search space in the specified time step interval  $K_{max}$ . The constraint (1a) is the position restriction constraint. This limits the mobile node to only be in one coordinate position at each time step. As denoted in the network model, the constraint (1b) is in place to denote the initial position of the mobile node with relation to the grid. The constraint (2) is the mobility restriction constraint. This eliminates the possibility of the mobile node moving to a farther position than physically possible. The mobile node cannot exceed  $\rho_x$  or  $\rho_y$  in the (x,y) coordinate direction within one iteration or time step. The constraints (3a - 3c) are the cell area coverage constraints. The constraint (3a) will determine whether a grid cell has been covered by a sensor nodes sensing radius. As long as a sensor node is present at  $x_{i+m, j+n}^k$  during an iteration  $k$ , the cells that are within its sensing radius  $r_s$  will be set as covered. The constraints (3b) and (3c) will determine the  $c_{i,j}$  value restrictions. In the model, a grid cell is either determined as covered or uncovered. Thus a value of zero is set as the value that represents an uncovered grid cell and a value of one is a covered cell.

### 3.3.2 MILP - Time Interval

The second MILP formulation proposed is a similar approach to the first. It is termed MILP-Time Interval. It is a similar approach to MILP-C, as it too finds an optimal area coverage,

however, this MILP will also optimize the number of time steps used to achieve that optimal coverage. The formulation and its components are listed below.

### **MILP-T (MILP-Time Interval)**

#### **Set of Variables**

$S^1$  = set of cells not covered by static nodes;

$S^2$  = set of cells covered by static nodes;

$S$  = set of all cells =  $S^1 \cup S^2$

$N_{\max}$  = total number of cells  $|S|$

$P$  = Percentage of coverage needed (Total coverage = 1, No coverage = 0)

$p_{i,j} = 1$  if there is static node at cell  $(i, j)$

$r_s$  = sensing radius of a node (in terms of number of cells)

$(i, j) \in S^2$  if  $(m, n)$  s.t.  $p(m, n) = 1$  &  $|m - i| \leq r_s$  &  $|n - j| \leq r_s$ .

$\rho_x (\rho_y)$  = maximum number of cells mobile node can travel in x (y) direction in 1 iteration.

$K_{\max}$  = maximum number of iterations possible.

#### **MILP Variable Listing**

##### **Binary variables:**

$x_{i,j}^k = 1$  if mobile node is located in cell  $(i, j)$  during iteration  $k$ .

##### **Continuous variables:**

$c_{i,j} = 1$  if cell  $(i, j)$  covered by mobile node at least once during all intervals.  $0 \leq c_{i,j} \leq 1$

#### **Objective Function**

$$\text{MIN } \sum_k \sum_{i,j \in S^1} x_{i,j}^k$$

#### **Constraint Functions**

##### **Subject to :**

##### **Position constraint**

$$\sum_{(i,j)} x_{i,j}^k = 1 \quad \forall k = 1, 2, 3 \dots K_{\max} \quad (1a)$$

$$\sum_{(i,j)} x_{i,j}^0 = 1 \quad (1b)$$

##### **Mobility constraint**

$$x_{i,j}^{k+1} \leq \sum_m \sum_n x_{i+m, j+n}^k \quad -\rho_x \leq m \leq \rho_x, -\rho_y \leq n \leq \rho_y, \quad \forall k = 1, 2, 3 \dots (K_{\max} - 1) \quad (2)$$

**Cell coverage constraint**

$$c_{i,j} \leq \sum_{m=-r_s}^{r_s} \sum_{n=-r_s}^{r_s} x_{i+m, j+n}^k \quad \forall i, j \in S^1, \forall k = 1, 2, 3 \dots K_{max} \quad (3a)$$

$$c_{i,j} \geq 0, \forall i, j \in S^1 \quad (3b)$$

$$c_{i,j} \leq 1, \forall i, j \in S^1 \quad (3c)$$

**Overall required coverage constraint**

$$\sum_{i,j \in S^1} c_{i,j} \geq P \cdot N_{max} \quad (4)$$

**Justification of MILP-T**

The objective function for MILP-Time Interval minimizes the number of iterations or time steps  $k$  when determining an optimally planned path. The values of  $x_{i,j}^k$  are combined to form the total number of iterations for the path planned for a mobile node. The constraint (1a) is the same position restriction constraint from MILP-C which restricts a mobile node to only be at one coordinate location at a time. Constraint (1b) is again initializing the initial position of the mobile node. Constraint (2) is also the same mobility constraint found in MILP-C which restricts the movement of a mobile node of up to  $\rho_x$  or  $\rho_y$  in the (x, y) coordinate direction during one iteration. Constraints (3a - 3c) are also the same as those found in MILP-C where they will allow the variables  $c_{i,j}$  to be determined whether they have been covered (denoted by a one) by a sensor node or left uncovered (denoted by a zero). The final constraint (4) is the area coverage requirement constraint. This constraint will ensure that the  $c_{i,j}$  values combined will be greater than a preset coverage requirement. The  $c_{i,j}$  values represent the grid cells covered and also the area covered by sensor nodes. This total must exceed a specified minimum which is the total number of grid cells available ( $N_{max}$ ) multiplied by a percentage factor ( $P$ ). Since our approach is looking for an optimal path, the percentage factor will be set to one, so that the full area coverage must be reached in order to permit the formulation objective value.

# CHAPTER 4

## Simulation Results

In this section, we explore the experimental simulation results collected from the two MILP formulation approaches MILP-Time Interval and MILP-Coverage. In order to validate the MILP formulation approach, simulations were conducted using different setup parameters to verify the method's performance as well as to determine the limitations of the method. Another way of validation will be to compare the performance of the approach against existing approaches.

### 4.1 Simulation Setup

The general process in which the path planning approach works is shown in Figure 9.

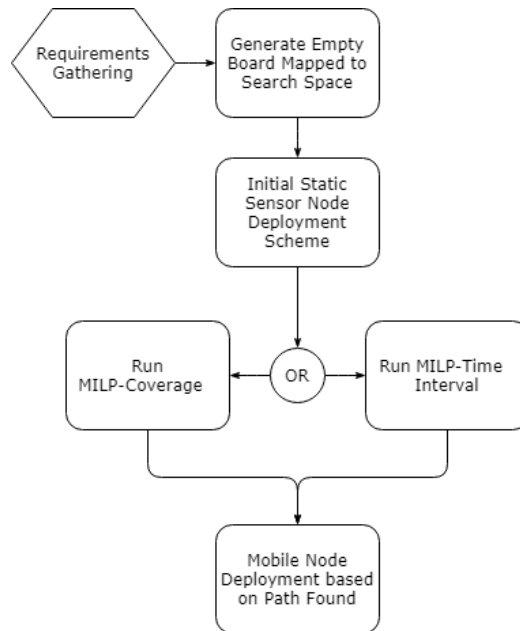


Figure 9. High Level Process of our Approach

First the requirements such as the physical grid information, the initial static node random deployment strategy and the number of mobile nodes needed are initialized. This information will vary depending on the application problem in question.

To simulate this thesis' work using MILP formulations we use the IBM ILOG CPLEX Optimization Studio which is shortened to CPLEX. CPLEX is a mathematical optimization software which is able to solve integer programming problems [25]. Another component necessary to utilize WSNs with the MILP formulation is a network grid that keeps track of the covered and uncovered areas of the search space and keeps track of the positions of the sensor nodes. To model our network grid, a simple text file is created which will contain and update the relevant network information necessary for the simulation runs. Furthermore, to simulate the routing of mobile nodes through the network we need the CPLEX solver to solve an optimal objective value for each of our formulations. In the process of evaluating our MILP formulation, we focus on the positions of each mobile node at each time step and the covered area of the search space. We do not focus on the communication between sensor nodes. For each simulation we record the MILP equations based on the input parameters, the positions of the mobile node at each time step and the area coverage at each time step.

Each simulation conducted begins with the creation of the search space grid and the setup file that dictates the behaviour of the simulation. The network grid contains the sensor node coordinate position location information as well as the information of which grid cells are uncovered or covered by the sensor nodes' sensing radius'. The static sensor nodes are added at time step zero as the initial random deployment for the simulation environment and their coordinate positions are relayed back to the network grid.



The next simulation step is to generate the setup file. This setup file will handle the specification of simulation parameters such as the dimensions of the search space grid, the number of static nodes at initial deployment, the movement speed of each sensor node and the sensing radius of each sensor node. Furthermore, it will generate the different files necessary to record area coverage and iteration usage results.

The main purpose of the setup file lies in the final creation of the lpfile. This file contains the MILP formulation equations which will be based on the search space grid and the setup parameters set by the user. The lpfile will contain the objective equation, the constraint equations and the variable declarations for the MILP formulation and will be the main file used in CPLEX. The setup file used to generate the lpfile must convert the formulation equations in code that CPLEX is able to process. An expansion of the equations is the first necessity in building the lpfile correctly.

For  $K_{max} = 4$ , and a 3x3 Grid:

$$c_{i,j} \leq \sum_{k=1}^{K_{max}} c_{i,j}^k \quad \forall i,j \in S^1 \longrightarrow$$

$$\begin{aligned} C_{0,0} - C_{1,0,0} - C_{2,0,0} - C_{3,0,0} - C_{4,0,0} &\leq 0 \\ C_{0,1} - C_{1,0,1} - C_{2,0,1} - C_{3,0,1} - C_{4,0,1} &\leq 0 \\ C_{0,2} - C_{1,0,2} - C_{2,0,2} - C_{3,0,2} - C_{4,0,2} &\leq 0 \\ C_{1,0} - C_{1,1,0} - C_{2,1,0} - C_{3,1,0} - C_{4,1,0} &\leq 0 \\ C_{1,1} - C_{1,1,1} - C_{2,1,1} - C_{3,1,1} - C_{4,1,1} &\leq 0 \\ C_{1,2} - C_{1,1,2} - C_{2,1,2} - C_{3,1,2} - C_{4,1,2} &\leq 0 \\ C_{2,0} - C_{1,2,0} - C_{2,2,0} - C_{3,2,0} - C_{4,2,0} &\leq 0 \\ C_{2,1} - C_{1,2,1} - C_{2,2,1} - C_{3,2,1} - C_{4,2,1} &\leq 0 \\ C_{2,2} - C_{1,2,2} - C_{2,2,2} - C_{3,2,2} - C_{4,2,2} &\leq 0 \end{aligned}$$

**Figure 10. Example Constraint Deconstruction**

Figure 10 shows an example of an expansion of an equation. The simulation is assumed to have an iteration limit of 4 iterations and is being run on a 3 by 3 grid space. The equation on the left is the formulation equation which is expanded using these parameters into the 8 lines of equations on the right side. A notable difference between the two sides is the placement of

variables. In CPLEX there must be a constant on the left hand side of the equation with the variables residing on the left hand side of the equation. Thus the formulation equation must be altered to account for this restriction. The lpfile will be prepared for CPLEX solving purposes when each equation is expanded based on the input parameters.

After the lpfile is complete, CPLEX is initialized with the halting condition which will determine when a simulation will end. This can be set as a threshold value or a time limit. The time limit will allow the simulation to run for that long and then will return the current best result, while the threshold value will allow the simulation to run until the current best result is within a percentage of the optimal possible solution. This halting condition was set to the lowest threshold value of 0% to force the solution to optimally find the best route for the mobile nodes while also reaching 100% area coverage. For later simulations this threshold is relaxed to allow for a close to 100% percent coverage within a more reasonable amount of time. After initializing CPLEX, the lpfile is read into a CPLEX problem object which will then be used to run the simulation. The simulations will return the optimal routes for the mobile nodes along with the results for the area coverage and iteration usage information in separate output files. The final step will be for the mobile nodes to move along their specified coverage optimizing route.

## **4.2 Formulation Performance**

This topic of using a WSN to cover a random search space to detect environmental changes does not have a standardized test or benchmark that can serve as a comparison base for our results. In the literature, the way to test input for WSNs is to choose a suitable grid size, sensing radius, movement parameter and number of nodes and then run simulations on that setup. Once the results are attained they may either be discussed at face value for performance or they can be compared to existing approaches on the same setup environment. As long as the

setup is feasible as a real world scenario, then any results found will be acceptable to show performance in those real world circumstances.

In terms of this thesis, both ways of testing inputs are completed. However, the difference of this approach is that it is supposed to serve as a benchmark for other approaches in terms of standalone total coverage percentage and total coverage percentage within the smallest number of iterations. Since this thesis uses an MILP formulation, the results should be optimal given the setup scenario. The benchmark comparison should only be for iterations and coverage since a comparison on time efficiency is not strived for in this thesis. An MILP formulation will most likely take more time to attain an optimal solution, thus it should be used to compare against an approach that is also solving a coverage problem using WSNs.

#### **4.2.1 Limitations of Results**

There are some limitations of using a MILP formulation to solve a problem with multiple parameters. MILP based methods used in large problem spaces tend to be computationally intractable. As the number of parameters increases, the number of equations the formulation generates also increases accordingly. Although it is able to attain the necessary optimal results for the test cases above, for cases with larger parameters the proposed MILP formulations may not converge to a solution. The main constraint lies in the grid size and the maximum number of iterations allowed. As the grid increases, two different variables ( $x$ ,  $y$ ) which denote the coordinates of the grid will increase. This will increase the number of equations for those that contain either or both variable. An increase in the number of iterations is also a detriment since the iterations needed for a mobile node to traverse a grid will increase with the expansion of the grid.

For this thesis, the maximum grid size that is feasible in terms of time efficiency is a 20 by 20 meter grid size. While testing the impact of the parameters of the formulation, it was found that after 20 by 20, the time to complete a simulation for 100% coverage was reaching into multiple hours. After the testing of grids up to 32 by 32, in some cases the formulation simulation would not be able to reach a solution at all due to the program halting. Thus, in order to manage this issue, a grid size of 20 by 20 was set as the maximum allowed size for a search space. To adapt this thesis' approach to larger search space fields, it would be appropriate to split the larger search space into smaller subsections. The MILP formulation would be simulated for each decomposed sub-grid. The resultant solutions could then be used to attain results for larger grids.

There are two main ways in which the separate results can be categorized. The first approach is to use one mobile node for the entire grid. Each subsection will generate its own path for the mobile node to move through. Thus the mobile node will need to follow along each of those paths to move through the entire grid. Since the MILP formulations will only deal with the subsections separately, after each calculation an extra number of iterations is needed for the mobile node to traverse from one subsection to the next. After moving to the new subsection the MILP will be run again to continue the mobile node traversal through each subsection area. This extra movement time between subsection can usually be minimized if the sensor node has a higher maximum speed than one meter per time step. As discussed in Chapter 2, the movement of sensor nodes should be kept low when they are sensing their environment since quicker movement may lead to missed detections of events. However, when moving between subsection there will be no sensing needed, thus it can move as quickly as possible to the new subsection grid. This first approach is mainly used for comparison between literature works since the vast

majority of simulations in the literature uses one mobile node. The second approach is to use one mobile node for each subsection of the grid. Since the formulation assumes a random starting location for the mobile node, this approach will allow the mobile node to act as if it is randomly placed at initial deployment. Then it will use the formulation to determine the optimal path within its subsection. This will allow each mobile node to be responsible for its own subsection but will lead to higher costs since more mobile nodes will be needed to cover each subsection of the total grid space.

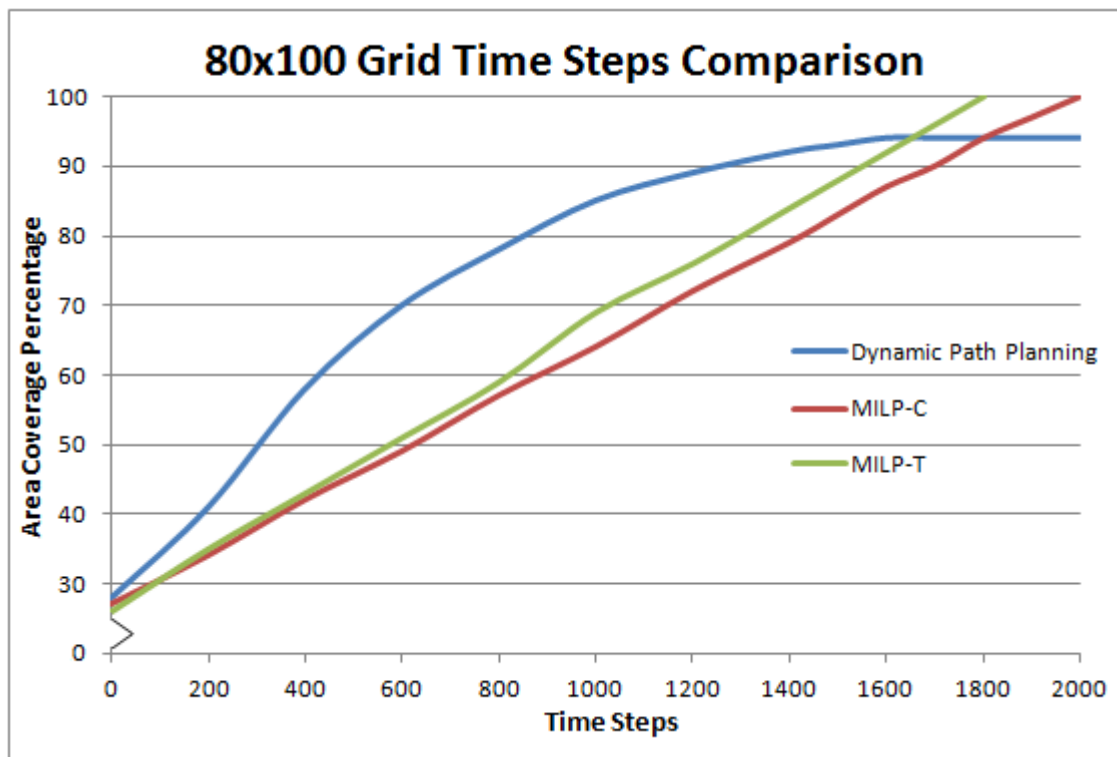
#### **4.2.2 Comparison with Existing Approaches**

In this section, we evaluate the performance of our approach by comparing it to other approaches in the literature that use WSNs for area coverage. The first paper that will serve as a comparison for performance against existing techniques will be [11]. This paper was discussed in Chapter 2 and deals with the Zoom algorithm being used to determine coverage holes surrounding static sensor nodes. The approach is named Dynamic Path Planning Algorithm. The mobile nodes will use this broadcasted information to determine the next location of the largest coverage hole. If there are no coverage holes nearby, the mobile node will move in an autonomous fashion determined by the user. This work is a good candidate for comparison since both their approach and ours use a path planning approach to determine where the mobile node should move.

The simulation setup used by this author is the initialization of a 100 by 80 grid with 100 randomly placed stationary sensor nodes. The sensing radius of each node in the network is set to 2 meters and the movement allowed is 1 meter per time step. The approach used is tested against a deterministic approach where the mobile nodes will systematically move through each of the grid spaces. The first simulation uses 1 mobile node and attained a coverage percentage of just

below 94% after 1500 iterations. The second simulation runs this approach against a random movement strategy and the deterministic strategy. The results found were that this approach reached around 85% coverage after 1000 iterations.

An identical simulation setup was used to compare our approach to the literature's approach. The results found were compiled into the graph of Figure 11.



**Figure 11. Comparison of proposed approaches with Dynamic Path Planning Algorithm**

MILP-C and MILP-T were both able to reach 100% area coverage at around 1800 and 2000 iterations respectively. MILP-C performed the slowest and also used more iterations than either the literature or MILP-T results. MILP-C is designed to be able to utilized an amount of iterations up to the amount of time steps a "standard" deterministic approach would need to attain full coverage. This fact is highlighted in this comparison where MILP-C used about 200 more iterations than MILP-T which optimizes iterations as well. From the results it is apparent

that the literature approach covers more area quicker than either MILP approach. This is due to the fact that the mobile node in the literature will path towards the next largest coverage hole after each broadcast. Thus the literature method will miss out on the smallest coverage holes and will end up leaving the smallest coverage holes uncovered. This is apparent from the literature results where the coverage increases rapidly but plateaus around 1500 iterations where the area coverage reaches 94%. This fact illustrates how the literature method may leave behind small coverage holes when guiding a mobile node so as to increase the area coverage in the short run. Thus if a 100% percent area coverage is necessary, MILP-T would be the most desirable method since it optimizes time step usage along with area coverage.

The second technique that we will use to compare the performance of our approach with is presented in [10]. This paper allows static nodes to bid for mobile nodes to move towards coverage holes within the static sensor node's vicinity. The second protocol introduced is the same strategy but it allows mobile nodes to extrapolate potential future positions. This protocol is termed a Proxy-based bidding protocol and is used as a comparison to our approach since they are both dealing with mobile nodes traversing the search space in order to maximize coverage. The difference lies in that their approach deals with mobile nodes moving in a dynamic fashion while ours is deterministic after the initial deployment. The comparison between the two approaches is valuable to see how our approach can be used as a benchmark to test against other approaches. Furthermore, this comparison will highlight the strengths and weaknesses of a dynamic approach over a deterministic one.

The simulation setup used in this paper is a 60 by 60 meter grid with 60 randomly placed static sensor nodes. The amount of mobile nodes was set as a percentage of the amount of static nodes placed, which ranges from 10% to 50%. The sensing radius is set to 6 meters. The

simulations were run based on the different amounts of mobile nodes introduced into the network grid. With the lowest 10% of mobile nodes, the results found were that the protocol achieved a coverage of 90%. As the number of mobile nodes increased, the coverage also increased, with the final coverage reaching 98% with 50% mobile nodes, which is 30 mobile nodes.

In order to compare these results against our approach, the simulation setup in [10] was mirrored to conduct our own simulations. Using identical parameters, the results found from each formulation was compiled into Table 1.

**Table 1. Comparison with Proxy-Based Bidding Protocol**

Percentage of Mobile Nodes	Percentage Area Coverage		
	MILP Formulations		Values from [10]
	MILP-C	MILP-T	
1	100%	100%	-
10	-	-	90%
15	100%	100%	92%
50	-	-	98%

Our approach cannot freely change the number of mobile nodes added at initial deployment. The only two simulation possibilities are a 1% mobile node usage, which would use one mobile node to traverse the entire grid space, and a 15% mobile node usage, which would place one mobile node in each subsection and the mobile nodes would only be responsible for traversing their subsection. From the table, it is observed that our approach outperforms this literature's method in every simulation. This comparison is rather simple since the result information displayed in the literature was very simple. They only highlighted the coverage percentage simulated against the amount of mobile nodes. The iterations used and the run time were both neglected, thus these points cannot be compared. However, this comparison is still

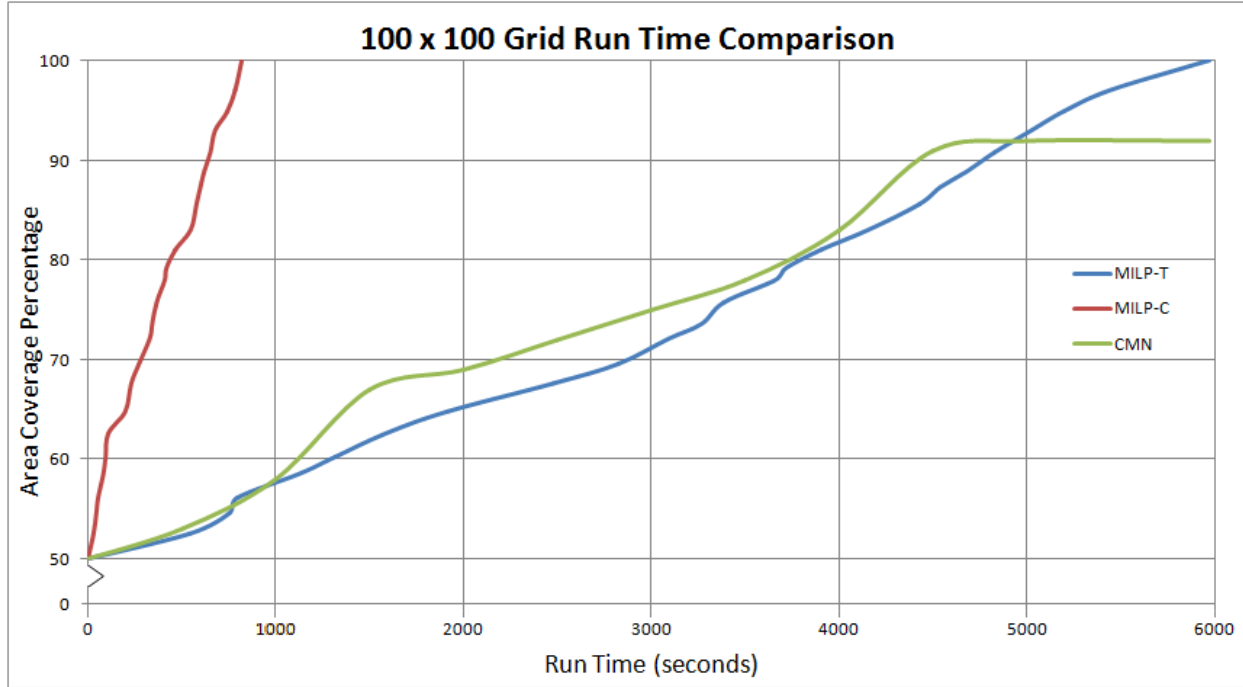


important. This is due to the fact that our approach outperformed the literature by reaching 100% coverage at 1% usage of mobile nodes. From the literature it was shown that as the percentage increased, their area coverage also increased. Thus our approach will need less mobile nodes to attain a higher area coverage than the literature approach. This will decrease cost while also increasing the performance of the WSN.

[7] will be the final paper that will be used as a comparison for our approach. The approach named CMN uses information on the distance between static nodes to determine the location of coverage holes. If the sensors are farther apart than the range of both of their sensing radius', then there must be a hole between them. The coverage holes will be ranked from largest to smallest and the mobile nodes will be placed in these locations, starting from the largest hole. This approach is a good comparison candidate to our approach since both use mobile nodes to cover coverage holes in the grid search space. Even though the literature approach uses a new mobile node each time to path towards coverage holes, it is still a good comparison point since it will show a runtime comparison of an approach that aims to improve area coverage against our own approach. In this literature work they use a ranking of coverage holes to move towards, while in this thesis we deterministically generate a set of optimal positions for the mobile nodes.

The simulations in this literature work are run on a 100 by 100 area grid space with 80 static nodes randomly deployed at initial deployment. The sensing radius for each node is set to a minimum of 5 meters and their technique was run for 6000 iterations. From their simulations, the maximum coverage achieved was around 92% at around 4500 iterations.

The simulation setup parameters were copied and the formulation simulations were run. The average results found using both MILP approaches is compiled in Figure 12.



**Figure 12. Comparison with CMN**

From this graph it is prevalent that our approach outperforms the literature approach in terms of area coverage. Whereas the literature reached 92% as a maximum area coverage at 4500 seconds, both of our approaches reached 100% area coverage. MILP-C was able to reach an area coverage of 100% after only 850 seconds which was much quicker than the literature or MILP-T. MILP-T performed quite close to how well the literature did, though the literature did seem to have a higher coverage between 1000 seconds and 4800 seconds. The difference lies in the fact that the literature approach adds mobile nodes into the largest coverage holes first while MILP-T will guide the mobile nodes through the search space in the least number of iterations regardless of coverage hole size.

These results show that MILP-C will converge to 100% area coverage quicker than MILP-T, however, it will do so using a higher number of iterations. On average the iterations of movement for a mobile node in MILP-C was 1100 iterations, while MILP-T used only around 780 iterations on average. Thus there will be some redundancy in the route generated in the

MILP-C solutions, while MILP-T will optimize the iterations used as well which will attempt to generate a route that attains 100% coverage while also doing so in the least number of time steps. The optimization of iterations in MILP-T will take more time, therefore a cost-benefit analysis must be used to determine whether MILP-C should be used to achieve a quick but suboptimal solution or MILP-T with the optimal solution but a much longer run time.

It is important to note that the experiments done in the literature and our own are not carried out on the same system. Therefore, although the simulation run time taken is much lower than the literature using MILP-C and comparable to the literature using MILP-T, the simulation does not provide a concrete comparison of run times. It does show however, that MILP approaches are able to achieve reasonable run time when finding optimal solutions.

### **4.2.3 Results with Varying Parameters**

The section below presents the results of our experiments to evaluate the area coverage performance of our proposed MILP-C and MILP-T. Various tests were conducted with different setup parameters and using different grid sizes. The setup parameters that vary are the number of static sensor nodes which is varied between 0 and 15 in intervals of fives, the travelling range or movement capabilities of the mobile nodes  $\rho_x = \rho_y$  which is varied between 1, 2 and 3 meters per second, and the sensing radius  $r_s$  of the sensor nodes which is varied between 3, 4 and 5. The coverage percentage was set to 100% coverage of the grid cells.

Two scenarios were generated to evaluate the MILP formulations' ability to optimize area coverage. The grid size configuration of the search space field was set to a 20 by 20 and 15 by 15 field as the two scenarios. Following the start of the simulation, the setup file creates randomly placed sensor nodes to simulate random initial static deployment which includes both the static and mobile nodes at the first time step. We performed 72 simulations per scenario each of which

applied a different combination of the WSN parameters listed above. The first 36 simulations are run using MILP-C and the latter half is run using MILP-T. The simulation results are compiled in Tables 2 - 5 below.

**Table 2. 15x15 Grid Comparison of Iterations used in Planned Route**

Movement Capability (meter/ time step)	Static Sensor Node Amount	MILP-Coverage			MILP-Time Interval		
		Sensing Radius (meters)					
		3	4	5	3	4	5
1	15	45	37	0	21	18	0
	10	45	37	11	32	10	7
	5	45	37	19	34	15	13
	0	45	37	25	37	26	19
2	15	25	21	0	12	10	0
	10	27	14	11	17	6	4
	5	27	22	14	18	8	7
	0	27	22	14	20	14	10
3	15	17	15	0	9	8	0
	10	20	15	10	14	5	3
	5	18	13	10	14	7	5
	0	20	15	10	15	11	7

Table 2 shows the results from both MILP formulations and details the iterations used by each of the routes found by each approach. The general trend noticeable from this table is that as the movement capability and sensing radius of the mobile nodes increases, the number of iterations in the route found decreases. This should be self evident since the ability to move farther in one time step and the ability to sense more of the area at a time will lead to less iterations used. Another fact evident from this table is that MILP-T finds an optimal number of iterations to use to achieve 100% area coverage while MILP-C will only sparingly use less iterations than the number of iterations a standard deterministic approach would use, which is the maximum iterations allowed.

**Table 3. 15x15 Grid Comparison of Run Time used by MILP formulations**

Movement Capability (meter/ time step)	Static Sensor Node Amount	MILP-Coverage			MILP-Time Interval		
		Sensing Radius (meters)					
		3	4	5	3	4	5
1	15	1.1	0.6	0	540.1	222.3	0
	10	8.6	0.4	0.4	1004.6	6.1	7.8
	5	9	0.9	0.3	1562.6	135.9	39.2
	0	15.2	5.4	1.6	2703.3	1807.5	452.7
2	15	2.8	1.7	0	402.7	39.5	0
	10	45.2	13.4	0.9	958.8	5.3	9
	5	6.3	1.8	1.3	1404.7	97.1	35.2
	0	153.7	13.3	4.4	2214.9	431.7	226.6
3	15	7.6	7.3	0	265.4	38.5	0
	10	112.8	15.8	0.5	913	4.5	1.2
	5	7.7	2.5	1.9	1246.8	96.8	1.7
	0	501.1	18.1	13.5	1726.6	228.8	68.4

Table 3 outlines the run time results from both MILP formulations. This table clearly shows that at the cost of achieving an optimal number of iterations using MILP-T comes at the cost of a much longer run time. However, as the movement capability increases alongside the sensing radius, the run time becomes much more feasible. There were some outliers but the general trend remains consistent overall.

For MILP-C the run time also decreases with the increase of the sensing radius. However, the opposite is true for MILP-C when increasing the movement capability. A smaller movement capability gives quicker results than a larger movement capability. This fact may be due to the fact that MILP-C tries to find any solution given the iteration limit while MILP-T tries to find the lowest amount of iterations to use as the solution. Thus when the movement capability increases there will be more possibilities for each approach. For MILP-T these new possible movements will allow it to more quickly find a solution by using the maximum movement capability to

traverse the grid space and only using a smaller movement when necessary. MILP-C does not have this distinction and it will most likely start by using the smallest movement and work its way to higher movement steps.

**Table 4. 20x20 Grid Comparison of Iterations used in Planned Route**

Movement Capability (meter/ time step)	Static Sensor Node Amount	MILP-Coverage			MILP-Time Interval		
		Sensing Radius (meters)					
		3	4	5	3	4	5
1	15	76	57	46	72	30	11
	10	80	56	43	73	41	15
	5	80	56	49	73	44	36
	0	80	57	50	75	47	36
2	15	45	32	20	35	16	6
	10	45	33	26	35	25	9
	5	44	33	28	42	23	20
	0	46	33	28	45	25	20
3	15	31	25	8	21	12	5
	10	31	23	21	24	17	6
	5	31	25	21	26	17	14
	0	31	25	21	28	18	14

Table 4 mirrors Table 2 in a comparison between time step usage of the two formulations. The distinction between them is the grid size has increased to 20 by 20 in Table 4. From this table it is apparent that the same trend is present to Table 2, where the number of time steps decreases with an increase in sensing radius or movement ability. MILP-C still also uses more iterations than MILP-T. Table 4 also shows that the number of iterations necessary increases as the grid size increases. The time step usage in Table 4 is on average around 1.5 to 2 times higher than the iterations used in Table 2. This shows that an increase in grid size will have no other interaction with sensing radius and movement capability other than to the increase the number of iterations necessary.

**Table 5. 20x20 Grid Comparison of Run Time used by MILP formulations**

Movement Capability (meter/ time step)	Static Sensor Node Amount	MILP-Coverage			MILP-Time Interval		
		Sensing Radius (meters)					
		3	4	5	3	4	5
1	15	412.1	4	0.5	2040	592.3	44.3
	10	377.7	13.1	1.5	2689	1350.2	342.2
	5	437.1	111.8	5	3656.2	2964.5	1350.2
	0	724.8	149.4	27.1	5610	4687.9	3593.7
2	15	3749.7	24.6	1.4	1870.8	531.2	27.1
	10	7802.6	34.6	4.2	2589.8	1215.1	163.4
	5	8499.4	702.6	7.5	3449.3	2664.2	1200.2
	0	23076.3	1096.3	47.4	5260.2	3965.2	3304.6
3	15	5315.5	56	5.4	1615.5	472.2	1.3
	10	11723.9	479.2	5.8	2129.3	1080.3	135.9
	5	20885	6011.6	28.4	2889.3	2368.3	1053.6
	0	72732.5	7069	128.8	3801.2	3587.2	2804.2

The final result chart Table 5 highlights the run times of each formulation in the larger grid. The results show a similar trend to Table 3 with MILP-C and MILP-T both lowering their run times with an increase in sensing radius. There is also the similar trend of MILP-T's decreasing run times with an increase of movement ability while MILP-C displays an increase in run times. The increase of run time for MILP-C seems to be much more drastic than in the 15 by 15 grid space. This shows that the increase of grid size using an MILP method will have adverse impacts on the run time of the MILP.

#### 4.2.4 Results with Comparison of MILP-C to Heuristic Methods

When running a simulation of MILP-C there will a variable ( $K_{max}$ ) which will denote the maximum number of iterations that the formulation is allowed to move the mobile node. Using a fixed cap for the number of iterations does not clearly show the performance of MILP-C since other methods may be able to outperform it given the same number of iterations. In order to

determine whether a suitable number of iterations is used as a maximum value for MILP-C, simulations are run using a Greedy Heuristic and Random Heuristic to achieve a performance comparison. The Greedy Heuristic method will move the mobile node so as to maximize coverage of uncovered areas for each time step, which the Random Heuristic will randomly move the mobile node at each time step. The pseudo code for each heuristic is given below in Figure 13 and 14.

---

```

1: procedure GreedyHeuristic (maxIterations)
2:   k = 1 #currentIteration
3:    $x_{i,j}^k$  = getMobileNodeInitialPosition()
4:   WHILE k < maxIterations
5:     maxCoverage = 0
6:     maxij = NULL;
7:     FOR each cell (i1, j1) within movement range (px / py) of  $x_{i,j}^k$ 
8:       cellij = (i1, i2)
9:       FOR each cell (i2, j2) within sensing range of cell (i1, j1)
10:        IF (cell (i2, j2) is uncovered)
11:          currentCoverage++
12:        END IF
13:      END FOR
14:      IF (currentCoverage > maxCoverage)
15:        maxCoverage = currentCoverage
16:        maxij = cellij
17:      END IF
18:    END FOR
19:    IF (maxij is NULL)
20:      maxij = random (cell within movement range)
21:    END IF
22:    k++
23:     $x_{i,j}^k$  = maxij
24:    updateGrid() #insert new position and update uncovered cells
25:  END WHILE
26: END procedure

```

---

**Figure 13. Pseudocode for Greedy Heuristic**



---

```

1: procedure RandomHeuristic (maxIterations)
2:   k = 1 #currentIteration
3:    $x_{i,j}^k = \text{getMobileNodeInitialPosition}()$ 
4:   WHILE k < maxIterations
5:     randX = random ( value between -px and +px)
6:     randY = random ( value between -py and +py)
7:     k++
8:      $x_{i,j}^k = x_{i+randX, j+randY}^{k-1}$ 
9:     updateGrid() #insert new position and update uncovered cells
10:  END WHILE
11: END procedure

```

---

**Figure 14. Pseudocode for Random Heuristic**

100 simulations were run on identical conditions to Results Section 4.3.3. The average results found were compiled within the tables below.

**Table 6. 15x15 Percentage of Uncovered Grid Area Covered by Heuristic**

Movement Capability (meter/ time step)	Static Sensor Node Amount	Greedy Heuristic			Random Traversal		
		Sensing Radius (meters)					
		3	4	5	3	4	5
1	15	90	42	-	31	31	-
	10	75	48	100	35	43	46
	5	78	84	40	29	41	38
	0	77	85	91	31	41	54
2	15	96	59	-	38	35	-
	10	80	69	100	40	41	50
	5	93	98	49	33	47	40
	0	75	88	90	37	49	54
3	15	96	64	-	48	43	-
	10	78	85	100	46	46	60
	5	90	99	60	40	49	42
	0	88	92	100	45	52	59

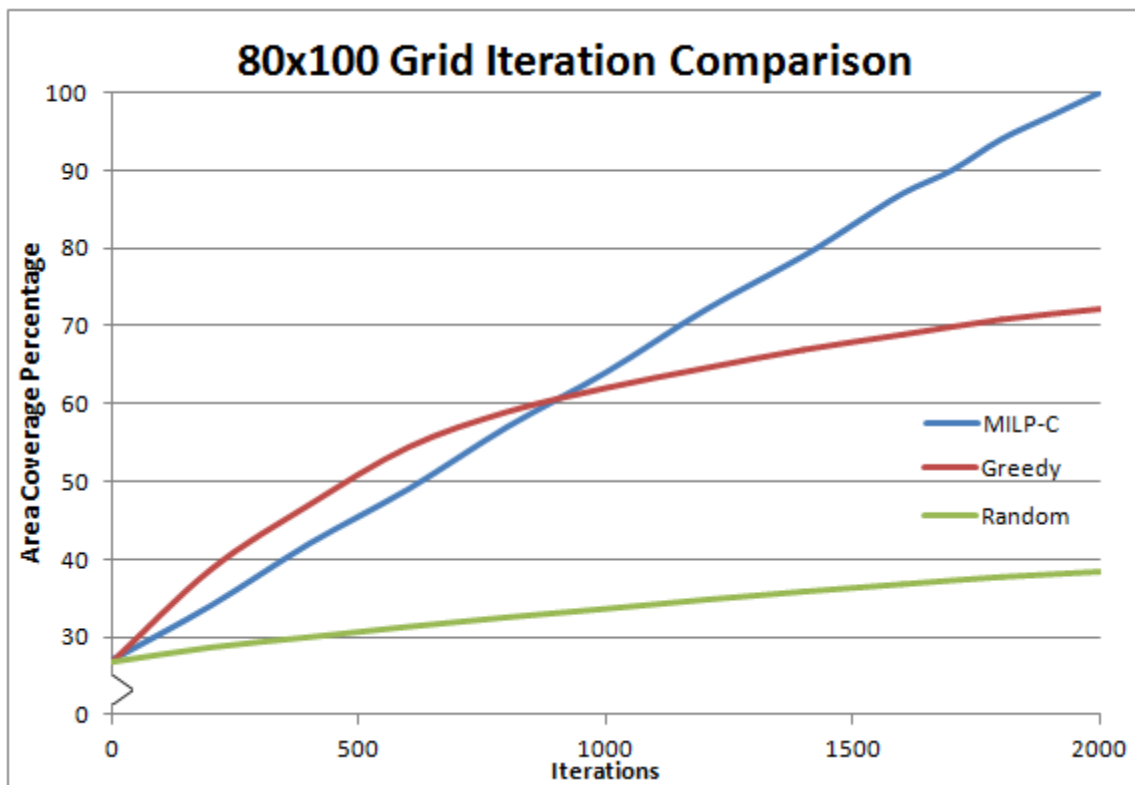
**Table 7. 20x20 Percentage of Uncovered Grid Area Covered by Heuristic**

Movement Capability (meter/ time step)	Static Sensor Node Amount	Greedy Heuristic			Random Traversal		
		Sensing Radius (meters)					
		3	4	5	3	4	5
1	15	72	71	93	20	38	58
	10	80	69	47	32	35	36
	5	83	73	56	21	21	21
	0	74	78	83	25	31	40
2	15	70	80	95	23	39	53
	10	95	78	67	38	36	38
	5	85	86	87	29	26	26
	0	79	79	85	33	35	43
3	15	78	92	96	28	45	50
	10	94	85	87	39	42	41
	5	97	88	93	34	35	34
	0	90	87	88	37	43	50

Tables 6 and 7 outline the percentage of uncovered area which is covered by the mobile node using a greedy or random heuristic method. The cells marked with a ( - ) are grids with no uncovered areas after initial deployment, therefore the total area is already covered prior to the running of the algorithm. It can be noted that there are a couple of instances where the greedy approach was able to achieve 100% coverage in the 15 by 15 grid with a sensing radius of 5. These instances are ones where there was a very small number of straightforward movement necessary to cover the remaining uncovered space. In every other case, the greedy and random heuristics were both unable to completely cover the uncovered cells given the same maximum number of iterations as MILP-C. This is due to a similar reason as in [7] where the greedy approach will attempt to move towards the locations which maximize covering uncovered cells while bypassing some uncovered cells which will leave coverage holes. The benefit of the greedy approach is that it takes under a second of run time to complete in each simulation,

however, it does not reach a 100% coverage and can sometimes be stuck at a local maxima when the area surrounding its current position is all covered cells. This will result in the heuristic randomly choosing a new destination node which may not leave the local maxima.

In order to test whether MILP-C uses an appropriate ( $K_{max}$ ) value for larger grid sizes, the simulation environment from literature work [11] was setup for both heuristic methods. The progress of area coverage from movement of mobile node is highlighted in Figure 15.



**Figure 15. 80x100 Grid Iteration Comparison of MILP-C against Heuristic Methods**

From Figure 15 it is apparent that both heuristic methods were unable to reach above 75% coverage using the same number of iterations as MILP-C. The greedy method was able to reach a higher area coverage faster than MILP-C until around 900 iterations since it will maximize area coverage at each time step which will leave many coverage holes behind. Furthermore, the greedy method ran into multiple instances of being trapped in areas with no

uncovered cells in which many iterations were wasted on finding a path towards uncovered cells.

After 1000 iterations MILP-C achieved a better area coverage and finally reached 100% coverage.

# CHAPTER 5

## Conclusion and Future Work

In this thesis, we have proposed using a WSN composed of a mixture of static and mobile sensor nodes to balance sensor cost with improved periodic area coverage. The WSN starts with an initial deployment of randomly placed sensor nodes which acts as the static infrastructure. Keeping the number of mobile sensor nodes placed to minimum is key to keeping the total cost of the WSN low while still attaining an optimal coverage. After the initial deployment, coverage holes tend to appear leading to incomplete supervision of the search space.

Both of our approaches use a mixed integer linear program to determine the routing positions of the mobile nodes. We designed a path planning approach to handle this problem in a deterministic fashion by using mobile nodes to plan the best route through coverage holes in the search space. The users may specify the percentage of coverage needed and the amount of sensor nodes available for their specific circumstances. The coverage holes are filled to the optimal extent and in the second approach also within the least number of iterations. These approaches of using mobile nodes to improve periodic area coverage allow each area of the search space to be covered at least once during the total time interval. Repeated simulations consistently highlight our approaches' ability as a benchmark method for optimizing area coverage.

In the future work, the application of MILP formulations can be explored for other purposes other than area coverage. As noted in the literature work, there are multiple different

performance measures such as energy usage and network lifetime that could also potentially use a MILP formulation to optimize as a benchmark.

Future work could also revolve around applications where the locations may require an increased degree of coverage depending on their area of significance. To solve this, the thesis method can be adjusted by altering the coverage variable typing from binary to another type such as integer, to allow for larger maximum values of coverage in an area.

Another promising direction to expand this research could be to explore other methods of partitioning the search space into balanced subsections. One possibility for balanced subsections could be allowing for different sized sections depending on the sensor node coverage in that section. The amount of static sensor node coverage in an area will determine the amount of time needed to find a solution, thus an analysis of the initial deployment can aid such a method.

Another way would be to allow a more simplistic deterministic method to handle areas with no coverage whatsoever since it will not matter which approach is used to fill empty locations with no obstacles.

# BIBLIOGRAPHY

- [1] Vecchio, Massimo, and Roberto López-Valcarce. "Improving area coverage of wireless sensor networks via controllable mobile nodes: A greedy approach." *Journal of network and computer applications* 48 (2015): 1-13.
- [2] Lambrou, Theofanis P., and Christos G. Panayiotou. "Collaborative event detection using mobile and stationary nodes in sensor networks." In *Collaborative Computing: Networking, Applications and Worksharing, 2007. CollaborateCom 2007. International Conference on*, pp. 106-115. IEEE, 2007.
- [3] Di Francesco, Mario, Sajal K. Das, and Giuseppe Anastasi. "Data collection in wireless sensor networks with mobile elements: A survey." *ACM Transactions on Sensor Networks (TOSN)* 8, no. 1 (2011): 7.
- [4] Ammari, Habib M., and Sajal K. Das. "Centralized and clustered k-coverage protocols for wireless sensor networks." *IEEE Transactions on computers* 61, no. 1 (2012): 118-133.
- [5] Rawat, Priyanka, Kamal Deep Singh, Hakima Chaouchi, and Jean Marie Bonnin. "Wireless sensor networks: a survey on recent developments and potential synergies." *The Journal of supercomputing* 68, no. 1 (2014): 1-48.
- [6] Liu, Benyuan, Olivier Dousse, Philippe Nain, and Don Towsley. "Dynamic coverage of mobile sensor networks." *IEEE Transactions on Parallel and Distributed systems* 24, no. 2 (2013): 301-311.
- [7] Zhu, Li, Chunxiao Fan, Huarui Wu, and Zhigang Wen. "Coverage Optimization Algorithm of Wireless Sensor Network Based on Mobile Nodes." *International Journal of Online Engineering (iJOE)* 12, no. 08 (2016): 45-50.
- [8] Akyildiz, Ian F., Weilian Su, Yogesh Sankarasubramaniam, and Erdal Cayirci. "Wireless sensor networks: a survey." *Computer networks* 38, no. 4 (2002): 393-422.
- [9] Lambrou, Theofanis P., and Christos G. Panayiotou. "Collaborative area monitoring using wireless sensor networks with stationary and mobile nodes." *EURASIP Journal on Advances in Signal Processing* 2009 (2009): 7.
- [10] Wang, Guiling, Guohong Cao, Piotr Berman, and Thomas F. La Porta. "Bidding protocols for deploying mobile sensors." *IEEE Transactions on Mobile Computing* 5 (2007): 563-576.
- [11] Lambrou, Theofanis P., Christos G. Panayiotou, Santiago Felici, and Baltasar Beferull. "Exploiting mobility for efficient coverage in sparse wireless sensor networks." *Wireless personal communications* 54, no. 1 (2010): 187-201.

- [12] Li, Xiaoyun, and David K. Hunter. "Distributed coordinate-free hole recovery." In *Communications Workshops, 2008. ICC Workshops' 08. IEEE International Conference on*, pp. 189-194. IEEE, 2008.
- [13] Debnath, Sunandita, Ashraf Hossain, Sultan Mahmood Chowdhury, and Abhishek Kumar Singh. "Effective sensing radius (ESR) and performance analysis of static and mobile sensor networks." *Telecommunication Systems* 68, no. 1 (2018): 115-127.
- [14] Howard, Andrew, Maja J. Matarić, and Gaurav S. Sukhatme. "Mobile sensor network deployment using potential fields: A distributed, scalable solution to the area coverage problem." In *Distributed Autonomous Robotic Systems 5*, pp. 299-308. Springer, Tokyo, 2002.
- [15] Akkaya, Kemal, and Mohamed Younis. "A survey on routing protocols for wireless sensor networks." *Ad hoc networks* 3, no. 3 (2005): 325-349.
- [16] Al-Karaki, Jamal N., and Ahmed E. Kamal. "Routing techniques in wireless sensor networks: a survey." *IEEE wireless communications* 11, no. 6 (2004): 6-28.
- [17] Wang, You-Chiun, Chun-Chi Hu, and Yu-Chee Tseng. "Efficient deployment algorithms for ensuring coverage and connectivity of wireless sensor networks." In *Wireless Internet, 2005. Proceedings. First International Conference on*, pp. 114-121. IEEE, 2005.
- [18] Ekici, Eylem, Yaoyao Gu, and Doruk Bozdog. "Mobility-based communication in wireless sensor networks." *IEEE Communications Magazine* 44, no. 7 (2006): 56-62.
- [19] Wang, You-Chiun, Chun-Chi Hu, and Yu-Chee Tseng. "Efficient deployment algorithms for ensuring coverage and connectivity of wireless sensor networks." In *Wireless Internet, 2005. Proceedings. First International Conference on*, pp. 114-121. IEEE, 2005.
- [20] Jain, Sushant, Rahul C. Shah, Waylon Brunette, Gaetano Borriello, and Sumit Roy. "Exploiting mobility for energy efficient data collection in wireless sensor networks." *Mobile Networks and Applications* 11, no. 3 (2006): 327-339.
- [21] Tunca, Can, Sinan Isik, Mehmet Yunus Donmez, and Cem Ersoy. "Ring routing: An energy-efficient routing protocol for wireless sensor networks with a mobile sink." *IEEE Transactions on Mobile Computing* 14, no. 9 (2015): 1947-1960.
- [22] Anastasi, Giuseppe, Marco Conti, Mario Di Francesco, and Andrea Passarella. "Energy conservation in wireless sensor networks: A survey." *Ad hoc networks* 7, no. 3 (2009): 537-568.
- [23] Boukerche, Azzedine, ed. *Algorithms and protocols for wireless sensor networks*. Vol. 62. John Wiley & Sons, 2008.
- [24] Silva, Ricardo, Jorge Sá Silva, and Fernando Boavida. "Mobility in wireless sensor networks—survey and proposal." *Computer Communications* 52 (2014): 1-20.



- [25] Gandham, Shashidhar Rao, Milind Dawande, Ravi Prakash, and Subbarayan Venkatesan. "Energy efficient schemes for wireless sensor networks with multiple mobile base stations." In *Global telecommunications conference, 2003. GLOBECOM'03. IEEE*, vol. 1, pp. 377-381. IEEE, 2003.
- [26] Ang, Kenneth Li-Minn, Jasmine Kah Phooi Seng, and Adamu Murtala Zungeru. "Optimizing energy consumption for big data collection in large-scale wireless sensor networks with mobile collectors." *IEEE Syst. J.* 12, no. 1 (2018): 616-626.
- [27] Ma, Ming, Yuanyuan Yang, and Miao Zhao. "Tour planning for mobile data-gathering mechanisms in wireless sensor networks." *IEEE Transactions on Vehicular Technology* 62, no. 4 (2013): 1472-1483.
- [28] Eledlebi, Khoulood, Dymitr Ruta, Fabrice Saffre, Yousof Al-Hammadi, and A. F. Isakovic. "A Model for Self-deployment of Autonomous Mobile Sensor Network in an Unknown Indoor Environment." In *Ad Hoc Networks*, pp. 208-215. Springer, Cham, 2018.
- [29] Huang, Mingfeng, Anfeng Liu, Ming Zhao, and Tian Wang. "Multi working sets alternate covering scheme for continuous partial coverage in WSNs." *Peer-to-Peer Networking and Applications* (2018): 1-15.
- [30] Gage, Douglas W. *Command control for many-robot systems*. Naval Command Control and Ocean Surveillance Center Rdt And E Div San Diego CA, 1992.
- [31] Mainwaring, Alan, David Culler, Joseph Polastre, Robert Szewczyk, and John Anderson. "Wireless sensor networks for habitat monitoring." In *Proceedings of the 1st ACM international workshop on Wireless sensor networks and applications*, pp. 88-97. Acm, 2002.
- [32] Jin, Yuan, Yong He, Guoqiang Fu, Aibing Zhang, and Jianke Du. "A non-retraction path planning approach for extrusion-based additive manufacturing." *Robotics and Computer-Integrated Manufacturing* 48 (2017): 132-144.
- [33] Dash, Dinesh. "Approximation algorithm for data gathering from mobile sensors." *Pervasive and Mobile Computing* 46 (2018): 34-48.
- [34] Borse, Mrs Savita V., Yogesh S. Patil, and Dinesh D. Patil. "A SYSTEM WITH LOAD SHARING TECHNIQUE VIA MOBILE NODE ROTATION FOR IMPROVING LIFETIME OF A WSN." *International Education and Research Journal* 4, no. 1 (2018).
- [35] Singh, Abhiram, and T. P. Sharma. "A survey on area coverage in wireless sensor networks." In *Control, Instrumentation, Communication and Computational Technologies (ICCICCT), 2014 International Conference on*, pp. 829-836. IEEE, 2014.

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